ASHRAE Guideline 24-2008R

Public Review Draft

Ventilation and Indoor Air Quality in Low-Rise Residential Buildings

First Public Review (February 2015)
(Complete Draft for Full Review)

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(This foreword is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE.)

FOREWORD

In 2003, ASHRAE published Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, the first stand-alone ventilation and indoor air quality (IAQ) standard specifically written for low-rise residential buildings. Although Standard 62.2 provides far more detailed residential ventilation requirements than were contained in the previous versions of Standard 62, the 62.2 project committee felt that the new standard by itself did not adequately address the need to provide information on achieving better IAQ in low-rise residential buildings. In writing Guideline 24, the committee was able to address IAQ and ventilation issues where consensus could not be achieved in Standard 62.2, and to provide explanatory and educational material that would be inappropriate in a document intended for code adoption.

While the title of Guideline 24—Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings—is nearly identical to that of Standard 62.2, this guideline's purpose and scope contain many significant differences from the standard. The purpose of the standard is limited to defining the roles of and minimum requirements for mechanical and natural ventilation systems and the building envelope intended to provide acceptable IAQ in low-rise residential buildings. While these roles and requirements are written with the intent of providing acceptable IAQ in low-rise residential buildings, the much broader purpose of this guideline is to provide information on achieving better IAQ in all types of dwelling units.

The scope of this guideline is also broader than the scope of the standard. Both scopes specify that the documents apply to residential buildings three stories or fewer in height above grade, including manufactured and modular houses. However, the standard's scope specifically excludes unvented combustion space heaters and provides a list of reasons that may prevent acceptable IAQ from being achieved, despite meeting all of the minimum requirements. Given its broader scope that address topics not included in the standard, the guideline goes beyond the standard's baseline objective of acceptable IAQ in providing information aimed at helping to achieve better IAQ.

Thus, in addition to providing informative background material on residential IAQ, this guideline addresses important residential IAQ issues that were not addressed in Standard 62.2 due to lack of consensus or other reasons. Some of these issues were addressed in pre-publication draft versions of Standard 62.2 and include carbon monoxide (CO) alarms, air distribution, better air filtration, and unvented combustion appliances. This guideline also provides useful information on topics such as verification of ventilation equipment performance and operations and maintenance which, though important, are not easily addressed in a standard intended for code adoption.

1. PURPOSE

1.1 This guideline provides information on achieving indoor air quality (IAQ) that may go beyond minimum requirements, i.e., better IAQ.

1.2 It also provides information relevant to ventilation and IAQ on envelope and system design, material selection, commissioning and installation, and operation and maintenance.

2. SCOPE

This guideline primarily applies to ventilation and IAQ for human occupancy in residential buildings three stories or fewer in height above grade, including manufactured and modular houses.

3. DEFINITIONS

When the following terms are used in this guideline, the definitions provided in this section apply.

acceptable indoor air quality: air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be contaminants at concentrations that are known to pose a health risk.

air cleaning**:** the use of equipment that removes particulate, microbial, or gaseous contaminants (including odors) from air.

air, exhaust**:** air discharged from any space to the outside by an exhaust system.

air, indoor**:** air in an occupiable space.

air, outdoor**:** air from outside the building that is taken into a ventilation system or that enters a space through infiltration or natural ventilation openings.

air, transfer**:** air that is moved from one occupiable space to another, usually through doorways or grilles.

air, ventilation**:** outdoor air that is delivered to a space to dilute airborne contaminants.
air change rate: airflow in volume units per hour divided by the volume of the space on which the air change rate is based in identical units (normally expressed in air changes per hour [ach]).

balanced system: one or more fans that supply outdoor air and exhaust building air at essentially equal rates.

bathroom**:** any room containing a bathtub, a shower, a spa, or a similar source of moisture.

better IAQ: Air that not only meets the definition of acceptable Indoor Air Quality, but also is expected to have reduced levels of contaminants of concern recommended by the selected cognizant authority.

breathing zone: the region within an occupied space between planes 3 and 72 in. (75 and 1800 mm) above the floor and more than 2 ft. (600 mm) from the walls or fixed air-conditioning equipment.

cognizant authority**:** an agency or organization that has the expertise and jurisdiction to establish and regulate concentration limits for airborne contaminants; or an agency or organization that is recognized as authoritative and has the scope and expertise to establish guidelines, limit values, or concentration levels for airborne contaminants.

concentration: the quantity of one constituent (i.e., contaminant) dispersed in a defined amount of another (i.e., volume of indoor air in a dwelling).

conditioned space**:** the part of a building that is capable of being thermally conditioned for the comfort of occupants.

contaminant**:** a constituent of air that may reduce acceptability of that air.

duct leakage: air leakage through unintentional holes in ductwork.

dwelling unit: a single unit providing complete, independent living facilities for one or more persons, including permanent provisions for living, sleeping, eating, cooking, and sanitation.

effective annual average infiltration rate: the constant air infiltration rate that would result in the same average indoor pollutant concentration over the annual period as actually occurs under varying conditions.

exhaust flow, net: the flow through an exhaust system minus the compensating outdoor air flow through any supply system that is interlocked to the exhaust system.

exhaust system: an unbalanced ventilation system consisting of one or more fans that remove air from the building, causing outdoor air to enter by ventilation inlets or normal leakage paths through the building envelope.
exposure: concentration of contaminant likely to be absorbed into the body.

forced-air conditioning system**:** a thermal conditioning system with a powered fan that uses air as the distribution medium in the building.

habitable space**:** building space intended for extended periods of human occupancy. Such space generally includes areas used for living, sleeping, dining, and cooking, but does not generally include bathrooms, toilets, hallways, storage areas, closets, or utility rooms.

high-polluting events: isolated and occupant-controllable events that release pollutants in excess quantities. Typical cooking, bathing, and laundry activities are not considered high-polluting events.

infiltration**:** the uncontrolled inward leakage of air through cracks and interstices in any building element, such as floors, walls, and ceilings, and around the windows and doors of a building.

intermittent ventilation: intermittently operated whole-building ventilation that is automatically controlled.

***kitchen*:** any room containing cooking appliances.

***mechanical cooling*:** reducing the temperature of a fluid by using vapor compression, absorption, or desiccant dehumidification combined with evaporative cooling or some other energy-driven thermodynamic cooling means. Indirect or direct evaporative cooling alone is not considered mechanical cooling.

***mechanical ventilation*:** the process of actively supplying or removing air to or from an indoor space by powered equipment such as motor-driven fans and blowers, but not by passive devices such as wind-driven turbine ventilators or mechanically operated windows.

***natural ventilation*:** ventilation occurring as a result of only natural forces, such as wind pressure or differences in air density, through intentional openings such as open windows and doors.

occupiable space: any enclosed space inside a building's pressure boundary and intended for human activities, including, but not limited to, all habitable spaces, toilets, closets, halls, storage and utility areas, and laundry areas.

***pressure boundary*:** primary air enclosure boundary separating indoor and outdoor air. For example, a volume that has more leakage to the outside than to the conditioned space would be considered outside the pressure boundary. Exposed earth in a crawlspace or basement shall not be considered part of the pressure boundary.

***readily accessible*:** capable of being quickly and easily reached for operation, maintenance, and inspection.
***return leakage*:** duct leakage in return (negative-pressure) ducts.

***source*:** an indoor object, person, or activity from which indoor air contaminants are released; or a route of entry of contaminants from outdoors or sub-building soil.

stack effect: infiltration caused by pressure differences that result from temperature differences between indoors and outdoors.

***supply leakage*:** duct leakage in supply (positive-pressure) ducts.

supply system: an unbalanced ventilation system consisting of one or more fans that supply outdoor air to the building, causing indoor air to leave by normal leakage paths through the building envelope.

***system*:** equipment and other components that collectively perform a specific function, such as mechanical cooling or ventilation.

time average airflow rate: the total volume of air provided during a period of time divided by the time period.

***toilet room*:** a space containing a toilet, water closet, urinal, or similar sanitary service.

***utility room*:** a laundry, lavatory, or other utility room containing sinks or washing equipment.

ventilation: the process of supplying outdoor air to or removing indoor air from a dwelling by natural or mechanical means. Such air may or may not have been conditioned.

4. INDOOR CONTAMINANTS

4.1 Background. The purpose of this guideline is to provide information on achieving better IAQ, giving its users a way to control airborne concentrations of indoor contaminants, and thus reduce occupant exposures to these substances.

ASHRAE Standard 62.2-2013 defines a contaminant as “a constituent of air that may reduce the acceptability of that air.” The definition is broad, but experience has shown that a broad definition is justified: many constituents of air, at high concentrations, can cause adverse effects in building occupants. For example, water vapor in the air is usually not considered a contaminant. Indeed, occupants prefer that some water vapor is contained in the air and complain of excessive dryness when the concentration of water vapor is too low, as it often is during winter in cold climates. On the other hand, when water vapor concentrations are high, mold growth can occur, causing allergic reactions in some occupants as well as structural degradation in the building. Seventy percent relative humidity at a building surface is often cited as the level above which mold growth can occur. This is impacted by both indoor humidity and surface temperature, which in turn is affected by insulation levels. ASHRAE has developed Standard 160-2009, *Criteria for Moisture-Control Design Analysis in Buildings*[105] that details surface relative humidity requirements to prevent the growth of mold. More importantly for practical purposes, Standard 160-2009 specifies indoor air design humidity (%RH) to prevent, mitigate, and reduce moisture damage in the building.

Achieving better IAQ requires that contaminant concentrations be controlled. This occurs in two general ways: minimizing sources of contaminants and/or providing effective removal of the contaminants. Contaminant concentrations increase when the rate at which the contaminants are delivered to the air is greater than the rate at which they are removed from that air.

Note: When IAQ problems exist in a building, it is tempting to consider only ventilation strategies as solutions to these problems. However, while ventilation is typically necessary, controlling contaminant sources is often a more effective strategy for reducing concentrations. Indeed, experience from many building investigations leads to the conclusion that IAQ problems are often the result of contaminant sources that are too large (delivery rates too high) and/or ventilation rates that are too small (removal processes too low).

Passive and active gas phase removal technologies provide additional strategies to reduce contaminant concentrations often using less energy than ventilation approaches.

Because of the importance of identifying contaminants and their sources, this section of the guideline provides an overview of the subject. It then lists a collection of limiting values that various agencies have specified for the concentrations of contaminants to maintain acceptable IAQ in occupied spaces.

4.2 Contaminants and Their Sources. Contaminants originate both indoors and outdoors. Outside air contaminants can be introduced into a building through unintentional leaks in the building envelope as well as through doors, windows, and ventilation intakes. Inside air contaminants can be emitted from many sources, including occupants, building materials and furnishings, appliances, biological organisms, and personal activities (e.g., from pet dander, cooking, and tobacco smoke). The types of household products used and general housekeeping practices employed can greatly influence the levels of indoor air contamination. Soil gases can also be a source of contaminants in buildings. See the *2013 ASHRAE Handbook—Fundamentals*[96], Chapter 11, Air Contaminants.

Common sources of residential contamination include building construction and maintenance materials, cleaning compounds, furnishings, wall and floor coverings, appliances, home office equipment and supplies, and human activities, including cooking, pets, and biological agents. For example, formaldehyde can be emitted from various materials and products, including:

- particle board,
- press-wood paneling,
- some carpeting and backing,
- some furniture and dyed materials,
- urea-formaldehyde insulating foam,
- some cleaners and deodorizers, and
- some textiles.

Legislative efforts have reduced the formaldehyde emissions from many of these products, and efforts continue to further reduce these emissions.

These issues are revisited in Section 8 of this guideline, where contaminant sources and the transport of contaminants are discussed in more detail.

4.3 Concentration Limits. Many organizations set pollutant concentration limits for various indoor spaces that serve different populations. This part of Section 4 summarizes this information, which is excerpted, edited, and updated from Appendix B of *ASHRAE Standard 62.1-2013, Ventilation for Acceptable Indoor Air Quality*.[2]

This discussion contains a number of air-quality guidelines and regulations issued by bodies other than ASHRAE. It should be very clear that ASHRAE is not proposing any contaminant concentration standard or guideline values.

This discussion also describes the source of the values and the context in which they were developed. Many of these were not developed specifically for the residential environment but are provided here for informational purposes.

4.3.1 Summary of Selected Air Quality Guidelines. It is typically not possible to eliminate all pollutants from the indoor environment. In order to provide guidance on acceptable exposure to contaminants that are known to pose health risks, quantitative thresholds for acceptable indoor concentrations and exposures are needed for the particular contaminants. When providing guidance using thresholds, these concentration and exposure values need to be documented and justified by reference to a cognizant authority as defined in this guideline. Such guidelines or other limiting values

can also be useful for diagnostic purposes. At present, no single organization develops acceptable concentrations or exposures for all indoor air contaminants, nor are values available for all contaminants of potential concern. A number of organizations offer guideline values for selected indoor air contaminants. These values have been developed primarily for ambient (i.e., outdoor) air, occupational settings, and, in some cases, for residential settings. They should be applied with an understanding of their bases and applicability to the indoor environment of concern. If an acceptable concentration or exposure has not been published for a contaminant of concern, a value may be derived through review of the toxicological and epidemiological evidence using appropriate consultation. However, the evidence with respect to health effects is likely to be insufficient for many contaminants.

Note: At present, there is no quantitative definition of acceptable or better IAQ that can necessarily be met by measuring one or more contaminants.

Table 4-1 presents selected standards and guidelines used in Canada, Germany, Europe, and the United States for acceptable concentrations of substances in ambient air, indoor air, and industrial workplace environments. Table 4-2 lists concentration values of interest for selected contaminants as general guidance for building design, diagnostics, and ventilation system design. These values are issued by cognizant authorities and have not been developed or endorsed by ASHRAE. The table is presented only as background information. Consultation should be sought before selecting a value for use in building design or diagnostics purposes. Satisfying one, some, or all of the listed values does not ensure that acceptable or better IAQ (as defined in this guideline) will be achieved.

Selection of a specific target concentration and exposure is best made by a team with wide experience in toxicology, industrial hygiene, and exposure assessment. As they review the specific concentrations listed in Tables 4-1 and 4-2, or others taken from other sources, designers should be mindful of the following:

- Standards and guidelines are developed for different purposes and should be interpreted with reference to the setting, population, time period, and purpose for which they were developed compared with that to which they are being applied.
- Not all standards and guideline values recognize the presence of susceptible groups or address typical populations found in residential buildings.
- When many chemicals are present in the air, as they almost always are in indoor air, then some way of addressing potential interaction of these chemicals is warranted. For additive effects, the reader is referred to the American Conference of Governmental Industrial Hygienists' (ACGIH) *Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices*[3] for guidance on the subject.

4.3.2 Guideline Values for Industrial Environments.

ACGIH Threshold Limit Values (TLVs®) have been applied to industrial workplace air contaminants[3,4] (reference 4 is the German counterpart). The ACGIH TLVs® represent maximum acceptable 8-hour, time-weighted averages (TWA); 15-minute short-term exposure limits (STEL); and instantaneous (ceiling) case limits. They are cited as concentration limits for many chemical substances and physical agents for industrial use. In light of the constantly changing state of knowledge, the ACGIH TLVs® and BEIs® (Biological Exposure Indices) values are updated annually. In the annual update the user is

cautioned, “The values listed in this book are intended for use in the practice of industrial hygiene as guidelines or recommendations to assist in the control of potential health hazards and for no other use.”

Caution must be used in directly extending the ACGIH TLVs® or other workplace guidelines to spaces covered by this guideline and to population groups other than workers. Industrial health practice attempts to limit worker exposure to injurious substances at levels that do not interfere with the industrial work process and do not risk the workers’ health and safety. There is not an intention to eliminate all effects, such as unpleasant smells or mild irritation. Further, the health criteria are not uniformly derived for all contaminants. Irritation, narcosis, and nuisance or other forms of stress are not uniformly considered as the basis for the concentration limits. This is because different organizations use different end points and because different contaminants have more or less information available on diverse end points of interest. The target population is also different from the occupants found in the spaces covered by this guideline. In contrast, occupants in residential buildings do not expect to have elevated concentrations of potentially harmful substances, nor are monitoring programs in place, as may be the case with industrial contaminants. In addition, the general population may have less choice about where they spend their time and includes those who may be more sensitive, such as children, asthmatics, allergic individuals, and the elderly. Because exposure limits for many contaminants in indoor residential environments have not been established, industrial thresholds are often used, but are substantially adjusted downward.

Application of industrial exposure limits would not necessarily be appropriate for other indoor environments, occupancies, and exposure scenarios. However, lacking exposure limits for a specific non-industrial target population, substantial downward adjustments to occupational limits have sometimes been used for residential exposure thresholds.

4.3.3 Guidelines for Substances in Outdoor Air. Guidelines have been developed for outdoor air for a number of chemicals and metals, as shown in many of the references. These values, including some metals, may be appropriate for some indoor environments, but they should be applied only after appropriate consultation. These guidelines also supply guidance concerning the quality of outside air, if there is suspicion that outdoor air may be contaminated with specific substances or if there is a known source of contamination nearby.[5]

4.3.4 Regulation of Occupational Exposure to Airborne Contaminants. Regulations of occupational exposure to workplace hazards are based on the results of accumulated experience with worker health and toxicological research and are carefully evaluated by groups of experts. Effects are examined in relation to exposure to the injurious substance. Exposure is defined as the mathematical product of the concentration of the contaminant and the time during which a person is subject to this concentration. Since concentration may vary with time, exposure is typically calculated across the appropriate averaging time, expressed as a TWA concentration, STEL, or ceiling limit. Regulations of the U.S. Occupational Safety and Health Administration (OSHA) are TWAs in most cases. Industrial exposures are regulated on the basis of a 40-hour workweek with 8- to 10-hour days. During the remainder of the time, exposure is anticipated to be substantially lower for the contaminant of concern. Application of industrial exposure limits would not necessarily be appropriate for other indoor settings, occupancies, and exposure scenarios. However, lacking exposure limits for a specific non industrial target population, substantial downward adjustments to occupational limits have sometimes been used.

4.3.5 Substances Lacking Guidelines and Standards. For indoor contaminants for which an acceptable concentration and exposure value has not been established by a cognizant authority, one approach has been to assume that some fraction of TLV® is applicable and would not lead to adverse effects or complaints in nonindustrial populations. This approach should not be followed without assessing its suitability for the contaminant of concern. In any event, if appropriate standards or guidelines do not exist, expertise should be sought to determine contaminant concentrations and exposures that are acceptable.

4.3.6 Human Response to Contaminant Exposures and Subjective Evaluation. Scientists have discovered a number of ways that airborne chemicals can cause irritation of mucosal tissue such as that found in the human nose and the upper airways. These irritation responses can occur after the "irritant receptor" is exposed to nonreactive compounds, to reactive compounds with a different pattern of dose-response relationships, and through allergic and other immunologic effects for which dose-response relationships have not been well defined. The theoretical models of these irritation mechanisms have not yet found their way into standard-setting processes.

One reason for this may be the recognition of susceptible populations. For example, individuals with atopy (allergies) report irritation at lower levels of exposures than individuals without allergies. A complicating factor is that the elderly, the young, and other more susceptible populations may differ in their response to irritating and odorous substances as compared with healthy adults.

Indoor air often contains complex mixtures of contaminants of concern such as environmental tobacco smoke[6,7], infectious and allergenic biological aerosols[8], human bioeffluents, and emissions from food preparation. Precise quantitative treatment of these contaminants can be difficult or impossible in most cases. Chemical composition alone may not always be adequate to predict reliably the reaction of building occupants to most common mixtures of substances found in indoor air. To some degree, adequacy of control may rest upon subjective evaluation. Panels of observers have been used to perform subjective evaluation of IAQ in buildings.

Many contaminants have odors or are irritants that may be detected by human occupants or visitors to a space. A group of untrained panelists is exposed to known concentrations of contaminants under controlled conditions. Generally the air can be considered acceptably free of annoying contaminants if 80 percent of a panel deems the air not to be objectionable under representative conditions of use and occupancy.

4.3.7 Estimating Health Impacts of Contaminant Exposure. Quantifying the impact of contaminant exposure is important for justifying acceptable IAQ and its components of source control, ventilation, and filtration. The Disability Adjusted Life Years (DALY) methodology does just that.

DALY is the sum of years of potential life lost due to premature death and productive years of life lost due to disability. Developed in 1990, the use of the DALY has become increasingly common in the public health field. Within the last decade, this metric has been used to evaluate the importance of ventilation and to demonstrate the negative health impacts of various contaminants.[114]

Using the DALY metric, Logue et al.[112] concluded: "The main air pollutants of concern for regulators setting residential ventilation standards are formaldehyde, acrolein, and $PM_{2.5}$." Logue goes on to state:

"This implies that whole-residence ventilation rates should be based on controlling formaldehyde and acrolein. Filtration of incoming or house air to remove $PM_{2.5}$ would substantially improve indoor air quality." Other substances may be a source of concern as well.

4.3.8 Additional Sources of Information. Additional information on common indoor contaminants may be found in Chapters 10, 11, and 12 of the *2013 ASHRAE Handbook—Fundamentals.*[96] Another good source of information is the *National Healthy Housing Standard*.[115]

TABLE 4-1 Comparison of Regulations and Guidelines Pertinent to Indoor Environments[a]

The substances listed in this table are common air contaminants in industrial and non-industrial environments. The values summarized in this table are from various sources with diverse procedures and criteria for establishing the values. Some are for industrial environments (OSHA, MAK, NIOSH, or ACGIH), others are for outdoor environments (NAAQS), others are general (WHO) or indoor residential environment-related (Canadian) values. The following explanations are intended to assist the reader by providing a brief description of the criteria for each agency's adoption of its guideline values.

- NAAQS: Outdoor air standards developed by the US EPA under the Clean Air Act. By law, the values listed in these regulations must be reviewed every five years. These concentrations are selected to protect not only the general population but also the most sensitive individuals.
- OSHA: Enforceable maximum exposures for industrial environments developed by OSHA (US Department of Labor) through a formal rule-making process. Once an exposure limit has been set, levels can be changed only through reopening the rule-making process. These permissible exposure limits (PELs) are not selected to protect most sensitive individuals.
- MAK: Recommended maximum exposures for industrial environments developed by the Deutsche Forschungs Gemeinschaft, a German institution similar to the National Institutes of Health. Levels are set on a regular basis, with annual reviews and periodic re-publication of criteria levels. These levels are enforceable in Germany and are not selected to protect the most sensitive individuals.
- Canadian: Recommended maximum exposures for residences developed by Health Canada, a Canadian institution similar to the National Institutes of Health. These are not intended to be enforced.
- WHO/Europe: Environmental (nonindustrial) guidelines developed in 1987 and updated in 1999 and again in 2005 by the WHO Office for Europe (Denmark). Intended for application both to indoor and outdoor exposure.

In 2010, WHO published guidelines for the protection of public health for a number of chemicals commonly present in indoor air.

- NIOSH: Recommended maximum exposure guidelines for industrial environments are developed by NIOSH (Centers for Disease Control) and published in a series of criteria documents. NIOSH criteria documents contain both a review of the literature and a recommended exposure limit (REL) guideline. These are not enforceable, are not reviewed regularly, and are not selected to protect most sensitive individuals. In some cases, they are set at levels above that deemed protective of health because commonly-available industrial hygiene practice does not reliably detect the substances at lower levels. (Note that methods used in nonindustrial settings are often more sensitive than NIOSH methods for industrial hygiene measurements.)
- ACGIH: Recommended maximum exposures for industrial environments developed by ACGIH's Threshold Limit Values (TLVs®) Committee. The committee reviews the scientific literature and recommends exposure guidelines. The assumptions are for usual industrial working conditions, 40-hour weeks, and single exposures. Surveillance practices for both exposures and biological responses are often in place in the work environments where these levels are used. These levels are not selected to protect most sensitive individuals. About half of the TLVs® are intended to protect against irritation. Published studies have shown that many of the TLVs® to protect against irritation actually represent levels where some or all of the study subjects did report irritation.[9,10]

The Table is not inclusive of all contaminants in indoor air, and achieving the listed indoor concentrations for all of the listed substances does not ensure odor acceptability, avoidance of sensory irritation or of all adverse health effects for all occupants. In addition to indoor contaminant levels, the acceptability of indoor air also involves thermal conditions, indoor moisture levels as they impact microbial growth, and other indoor environmental factors. ASHRAE is not selecting or recommending default concentrations.

Users of this table should recognize that unlisted noxious contaminants can also cause unacceptable indoor air quality, with regard to comfort (sensory irritation), odors, and health. When such contaminants are known or might reasonably be expected to be present, selection of an acceptable concentration and exposure may require reference to other guidelines or a review and evaluation of relevant toxicological and epidemiological literature.

TABLE 4-1 Comparison of Regulations and Guidelines Pertinent to Indoor Environments[a]

	Enforceable and/or Regulatory Levels			Non-enforced Guidelines and Reference Levels			
	NAAQS/EPA (ref. 11)	OSHA (ref. 12)	MAK (ref. 4)	Canadian (ref. 13,14)	WHO/Europe (ref. 15)	NIOSH (ref. 16)	ACGIH (ref. 3)
Carbon dioxide		5,000 ppm	5,000 ppm 10,000 ppm [15min]			5,000 ppm 30,000 ppm [15min]	5,000 ppm 30,000 ppm [15min]
Carbon monoxide[c]	9 ppm [g] 35 ppm [1hr] [g]	50 ppm	30 ppm 60 ppm [15min]	10 ppm [24hr] 25 ppm [1hr]	90 ppm [15min] 31 ppm [1hr] 8.7 ppm [8hr] 6.1 ppm [24hr]	35 ppm 200 ppm [C]	25 ppm
Formaldehyde[h]		0.75 ppm 2 ppm [15min]	0.3 ppm 1 ppm[i]	0.1 ppm [1hr] 0.04 ppm [8hr] [b]	0.1 mg/m^3 (0.081 ppm) [30 min][p]	0.016 ppm 0.1 ppm [15min]	0.3 ppm [C]
Lead	0.15 µg/m^3 [3 months][i]	0.05 mg/m^3	[s]		0.5 µg/m^3 [1yr]	0.05 mg/m^3	0.05 mg/m^3
Nitrogen dioxide	0.05 ppm [1yr] 0.1 ppm [1hr]	5 ppm [C]	0.5 ppm 1 ppm [15min]	0.05 ppm [24hr] 0.25 ppm [1hr]	0.1 ppm[1hr] 0.02 ppm [1 yr]	1 ppm [15min]	0.2 ppm
Ozone	0.075 ppm	0.1 ppm	[j]	0.02 ppm	0.05 ppm (100µg/m^3)	0.1 ppm [C]	0.05 ppm[k] 0.08 ppm[l]

	Enforceable and/or Regulatory Levels			Non-enforced Guidelines and Reference Levels			
	NAAQS/EPA (ref. 11)	OSHA (ref. 12)	MAK (ref. 4)	Canadian (ref. 13,14)	WHO/Europe (ref. 15)	NIOSH (ref. 16)	ACGIH (ref. 3)
							0.1 ppm[m] 0.2 ppm[n]
Particles[e] <2.5 µm MMAD[d]	12 µg/m³[1 yr] 35 µg/m³ [24 hrs]	5 mg/m³	0.3 mg/m³ for <4 µm	minimize exposure[q]	12 µg/m³[1 yr] 35 µg/m³ [24 hrs]		3 mg/m³
Particles[e]<10 µm MMAD[d]	50 µg/m³ [1yr] 150 µg/m³ [24hr] [g]		4 mg/m³		12 µg/m³[1 yr] 35 µg/m³ [24 hrs]		10 mg/m³
Radon	4 pCi/liter [1yr] [f]			200 Bq/m³ [1yr][r]			
Sulfur dioxide	0.075 ppm [1hr] 0.5 ppm [3hr] [g]	5 ppm	1 ppm 1 ppm[i]	0.38 ppm [5min] 0.019 ppm	0.008 ppm [24h] 0.19 ppm [10min]	2 ppm 5 ppm [15min]	0.25 ppm [15min]
Total Particles[e]		15mg/m³					

The user of any value in this table should take into account the purpose for which it was adopted and the means by which it was developed.

[a] [ ] Numbers in brackets refer to either a ceiling or to averaging times of less than or greater than 8 hours (min = minutes; hr = hours; y = year; C = ceiling, L = long-term). Where no time is specified, the averaging time is 8 hours.

[b] The 1 hour target is based on eye irritation effect and the 8-hour target is based on respiratory symptoms in children.

[c] As one example, regarding the use of values in this table, readers should consider the applicability of carbon monoxide concentrations. The concentrations considered acceptable for nonindustrial, as opposed to industrial, exposure, are substantially lower. These lower concentrations (in other words, the ambient air quality standards, which are required to consider populations at highest risk) are set to protect the most sensitive sub-population, i.e., individuals with pre-existing heart conditions.

[d] MMAD = mass median aerodynamic diameter in microns (micrometers). Less than 3.0 µm are considered respirable; less than 10 µm are considered

inhalable.

[e] Nuisance particles not otherwise classified (PNOC), not known to contain significant amounts of asbestos, lead, crystalline silica, known carcinogens, or other particles known to cause significant adverse health effects.

[f] See Table 4-2 for USEPA guideline.

[g] Not to be exceeded more than once per year.

[h] The U.S. Department of Housing and Urban Development adopted regulations concerning formaldehyde emissions from plywood and particleboard intended to limit the airborne concentration of formaldehyde in manufactured homes to 0.4 ppm. [24 CFR Part 3280, HUD Manufactured Home Construction and Safety Standards]

[i] Never to be exceeded.

[j] Carcinogen, no maximum values established.

[k] TLV® for heavy work.

[l] TLV® for moderate work.

[m] TLV® for light work.

[n] TLV® for any work, ≤2 hours

[p] Epidemiological studies suggest a causal relationship between exposure to formaldehyde and nasopharyngeal cancer, although the conclusion is tempered by the small numbers of observed and expected cases. There are also epidemiological observations of an association between relatively high occupational exposures to formaldehyde and sinonasal cancer.

[q] To address the main indoor sources, use a stove top fan while cooking and do not allow smoking indoors.

[r] Undertake remediation efforts if this annual average concentration in occupied areas is exceeded.

[s] No workplace air maximum concentration values. There are biological tolerance values (blood concentrations) for men and women.

TABLE 4-2 Concentration of Interest for Selected Contaminants

The substances listed in this table are common air contaminants of concern in nonindustrial environments. The target concentrations that have been set or proposed by various national or international organizations concerned with health and comfort effects of outdoor and indoor air are listed for reference only. The table is not inclusive of all contaminants in indoor air, and achieving the target indoor concentrations for all of the listed substances does not ensure freedom from sensory irritation or from all adverse health effects for all occupants. However, field experience in buildings has generally shown that when thermal conditions meet ANSI/ASHRAE Standard 55, when outdoor ventilation rates are equal to or greater than the minimum rates prescribed in this standard, when moisture levels of indoor and HVAC surfaces are low enough to prevent microbial growth, and when the contaminants in this table are below the guideline levels, then air quality can be expected to be perceived as acceptable by a majority of occupants. ASHRAE is not selecting or recommending default concentrations.

Health or comfort effects that are the basis for the guideline levels are listed in the "comments" column. For design, the goal should be to meet the guideline levels continuously during occupancy, since people spend the great majority of their time indoors.

Users of this table should recognize that unlisted noxious contaminants can also cause unacceptable indoor air quality, with regard to comfort (sensory irritation), odors, and health. When such contaminants are known or might reasonably be expected to be present, selection of an acceptable concentration and exposure may require reference to other guidelines or a review and evaluation of relevant toxicological and epidemiological literature. (Table 4-2 summarizes some of this literature.)

(Note: Reference numbers that are followed by [c] and [m] list the concentrations of interest [c] and measurement methods [m].)

TABLE 4-2 Concentrations of Interest for Selected Contaminants

CONTAMINANT	SOURCES	CONCENTRATIONS OF INTEREST	COMMENTS	REFERENCES
CARBON MONOXIDE (CO)	Leaking vented combustion appliances Unvented combustion appliances Parking garages Outdoor air	9 ppm (8-hr)	Based on effects on persons with coronary artery disease, average exposure for 8 hours. Based on common practice, indoor concentrations exceeding outdoor concentrations by 2-5 ppm may merit further investigation. Source - burning of gasoline, natural gas, coal, oil etc. Health Effects - reduces ability of blood to bring oxygen to body cells and tissues; cells and tissues need oxygen to work. Carbon monoxide may be particularly hazardous to people who have heart or circulatory problems and people who have damaged lungs or breathing passages.	11 [c] 17 [m]
FORMALDEHYDE (HCHO)	Pressed/composite wood products Furniture and Furnishings	0.1 mg/m^3 (0.081 ppm) (30 min and chronic)	Based on irritation of sensitive people, 30-minute and chronic exposure (WHO).	15 [c]17, 18 [m]

CONTAMINANT	SOURCES	CONCENTRATIONS OF INTEREST	COMMENTS	REFERENCES
		45 ppb (55 µg/m³) (1 h) 7.3 ppb (9 µg/m³) (8 h and chronic) 16 ppb	Acute, 8-hour, and chronic noncancer Reference Exposure Levels (RELs) developed based on current scientific database (Cal-EPA, OEHHA), Health Effects - Acute and chronic inhalation exposure to formaldehyde in humans can result in eye, nose, and throat irritation, respiratory symptoms, and sensitization. Human studies have reported an association between formaldehyde exposure and lung and nasopharyngeal cancer. In 2004, the International Agency for Research on Cancer (IARC) concluded that “formaldehyde is carcinogenic to humans [Group 1), on the basis of *sufficient* evidence in humans and *sufficient* evidence in experimental animals.” The U.S. Department of Health & Human Services in their National Toxicology Program’s 12th Report on Carcinogens classifies formaldehyde as a “known to be a human carcinogen”. Specific cancers cited were: sinonasal, nasopharyngeal and lymphohematopoietic (specifically myeloid leukemia) cancers. (U.S. DHHS, 2011) FEMA Procurement Specification for Manufactured Homes	20 21, 22, 23 U.S. DHHS, 2011
LEAD (Pb)	Paint dust Outdoor air	0.15 µg/m³	Based on adverse effects on neuropsychological functioning of children, average exposure for 3 months Sources - leaded gasoline (being phased out), paint (houses, cars), smelters (metal refineries); manufacture of lead storage batteries. Health Effects - brain and other nervous system damage; children are at special risk. Some lead-containing chemicals cause cancer in animals. Lead causes digestive and other health problems. Environmental Effects - Lead can harm wildlife. Although not a airborne number, EPA has established settled lead dust levels for residential settings: 40 µg/ft² for floors, 250 µg/ft² for interior	11 [c] 11 [m] 23 116

CONTAMINANT	SOURCES	CONCENTRATIONS OF INTEREST	COMMENTS	REFERENCES
			windowsills,400 µg/ft² for exterior window troughs. Bare Soil lead levels are 400 ppm for play areas and 1200ppm for non-play yard areas.	
NITROGEN DIOXIDE (NO_2)	Leaking vented combustion appliances Unvented combustion appliances Outdoor air	100 µg/m³ 200 µg/m³	Based on providing protection against adverse respiratory effects, average exposure for one year. Sources - burning of gasoline, natural gas, coal, oil etc. Cars are an important source of NO_2 outdoors and cooking and water and space heating devices are important sources indoors. Health Effects - lung damage, illnesses of breathing passages and lungs (respiratory system). Environmental Effects - nitrogen dioxide is a component of acid rain (acid aerosols), which can damage trees and lakes. Acid aerosols can reduce visibility. Property Damage - acid aerosols can eat away stone used on buildings, statues, monuments, etc. 24-hour average to prevent exposures during use of combustion appliances such as space-heating devices and gas stoves.	11 [c] 17 [m] 23
ODORS	Occupants, VOC sources (including fungal sources such as mold) Outdoor air	Predicted (or measured) acceptability to 80% or more of occupants or visitors	For sources other than people (except hygiene for body odors), source control is recommended.	6, 24, 25, 26 [c] 17 (for CO_2), 27 (for odor) [m]

CONTAMINANT	SOURCES	CONCENTRATIONS OF INTEREST	COMMENTS	REFERENCES
OZONE (O_3)	Electrostatic appliances Office machines Ozone generators Outdoor air	100 µg/m^3 (50 ppb) 10 ppb	Based on 25% increase in symptom exacerbations among adults or asthmatics (normal activity), 8-hr exposure (WHO); continuous exposure (FDA). Ozone present at levels below the concentration of interest may contribute to the degradation of indoor air quality directly and by reacting with other contaminants in the indoor space Ground-level ozone is the principal component of smog. Sources – outdoors from chemical reaction of pollutants; VOCs and NO_x; indoors from photocopiers, laser printers, ozone generators, electrostatic precipitators, and some other air cleaners. Health Effects - breathing problems, reduced lung function, asthma, irritates eyes, stuffy nose, reduced resistance to colds and other infections, may speed up aging of lung tissue. Environmental Effects – outdoors ozone can damage plants and trees; smog can cause reduced visibility; Property Damage - indoors and outdoors ozone damages natural and synthetic rubbers, plastics, fabrics, etc. Increased mortality found above 20 ppb, “safe O_3 levels would be lower than 10 ppm” Bell (2006). Environmental Health Committee Emerging Issues Brief	15, 28[c] 28 [m] 23 29, 30
PARTICLES ($PM_{2.5}$)	Combustion products, cooking, candles, incense, resuspension, and outdoor air	12 µg/m^3	$PM_{2.5}$ identified as the most significant indoor contaminant in terms of chronic health impact in residences.	11, 31

CONTAMINANT	SOURCES	CONCENTRATIONS OF INTEREST	COMMENTS	REFERENCES
PARTICLES (UFP)	Cooking Diesel and car exhaust Gas Appliances Fire Places Candles	No regulatory level Levels in homes during cooking can be >500 times background levels	Ultrafine particles (UFP) are smaller than 0.1 microns (μm). UFPs have been shown to increase mortality from cardiovascular and respiratory disease (Rim et al.). UFPs can be removed using MERV 13 filters and higher, and by exhausting sources of indoor UFPs (electric and gas cooking appliances, and all gas appliances).	32
RADON (Rn)	Soil gas	4 pCi/liter[a]	Based on lung cancer, average exposure for 1 year.	33 [c,m] 34 [m]
SULFUR DIOXIDE (SO_2)	Unvented space heaters (kerosene) Outdoor air	175 ppb (10 min) 75 ppb (1 hr.) 8 ppb (24 hr.)	Based on protecting against respiratory morbidity in the general population and avoiding exacerbation of asthma. Source - burning of coal and oil, especially high-sulfur coal from the Eastern United States; industrial processes (paper, metals). Health Effects - breathing problems, may cause permanent damage to lungs. Environmental Effects - SO_2 is a component of acid rain (acid aerosols), which can damage trees and lakes. Acid aerosols can also reduce visibility. Property Damage - acid aerosols can eat away stone used in buildings, statues, monuments, etc.	11 [c] 11 [m] 23

CONTAMINANT	SOURCES	CONCENTRATIONS OF INTEREST	COMMENTS	REFERENCES
TOTAL VOLATILE ORGANIC COMPOUNDS (TVOCs)	New building materials and furnishings Consumable products Maintenance materials Outdoor air	Precise guidance on TVOC concentrations cannot be given	A variety of definitions of TVOC have been employed in the past. There is insufficient evidence that TVOC measurements can be used to predict health or comfort effects. In addition, odor and irritation responses to organic compounds are highly variable. Furthermore, no single method currently in use measures all organic compounds that may be of interest. Therefore, some investigators have reported the total of all measured VOCs as the Sum VOC in order to make explicit that the reported value does not represent the total of all VOCs present. Some of the references included here use this method for presenting VOC measurement results. Setting target concentrations for TVOC is not recommended. Setting target concentrations for specific VOCs of concern is preferred.	17 [m] 35 [c] 18, 36, 37 38, 39
Volatile Organic Compounds (VOCs)	New building materials and furnishings Consumable products Maintenance and cleaning products Outdoor air	Should be determined for each individual compound CA OEHHA lists Reference Exposure Limits for many compounds	Individual volatile organic compounds may be contaminants of concern. Concentrations of concern range from less than 1 part per billion (ppb) for some very toxic compounds or for compounds having very low odor thresholds up to concentrations several orders of magnitude higher. Not all compounds can be identified, and toxicological data are incomplete for many compounds.	17 [m] 30 [m] 40 [m] 18, 25, 37, 41-39, [c] 27, 44-46 47

[a] The USEPA has promulgated a guideline value of 4 pCi/L indoor concentration. This is not a regulatory value but an action level where mitigation is recommended if the value is exceeded in long-term tests.

CONVERSION FACTORS[48]

Parts per million and mass per unit volume

Measurements of indoor airborne concentrations of substances are generally converted to standard conditions of 77°F (25°C) and 29.92 in. Hg (101.325 kPa) pressure. Vapors or gases are often expressed in parts per million (ppm) by volume or in mass per unit volume,

Concentrations in ppm can be converted to mass per unit volume values as follows:

ppm x molecular weight/24,450 = mg/L

ppm x molecular weight/0.02445 = μg/m^3

ppm x molecular weight/24.45 = mg/m^3

ppm x molecular weight/28.3/24,450 = mg/ft^3

5. BUILDING AIRFLOW FUNDAMENTALS

5.1 Introduction. Airflow in buildings can be categorized according to the primary driving forces that cause them, including natural infiltration and induced airflow. Natural infiltration is airflow driven by environmental conditions, whereas induced airflows result from the operation of mechanical or combustion devices in dwellings, such as ventilation fans, heating and cooling systems, fireplaces, and certain other combustion appliances. This section provides a fundamental primer on building airflow that can be used as an underlying context for other portions of this guideline.

5.2 Unintentional Pathways. For air to flow, both a pressure difference and a pathway are required. We have limited control over pressures, and it would be virtually impossible to always prevent any pressure difference from occurring. Therefore, before describing the airflow mechanisms, the pathways that air travels to enter a building should be understood.

In any building there is a pressure boundary, which is the set of surfaces that functions to keep indoor air in and outdoor air out. These surfaces should, in general, align with the insulated surfaces to form the thermal boundary of the building. However, some penetrations through the pressure boundary will remain.

These penetrations occur from a wide range of causes, such as gaps around plumbing, ducts, and wires. Most building materials are inherently porous (some more so than others), allowing air to move through them. Anything that penetrates the pressure boundary, such as fixtures for recessed lights and ventilation fans, can allow some air leakage. Windows and doors can also create gaps in the pressure boundary. Flues are another pathway through which air may travel.

The air that gets into the home through these gaps can come from any of a number of other spaces, such as crawl spaces, basements, garages, and attics. In addition, different rooms within the home are interconnected via the floor, wall, and ceiling cavities, allowing air that enters at one location to travel to another region of the home.

The leakiness of a building can be evaluated by direct measurement. The primary airtightness test for residential buildings is the blower door test.[49] The concentration decay method as using a tracer gas as specified in ASTM Standard E 741-11 is another option.[108]

5.3 Natural Infiltration. Natural infiltration occurs due to temperature differences between indoors and outdoors (stack effect) and wind. Infiltration in mild climates is more likely to be wind-dominated, whereas infiltration in more severe climates (both cold and hot) is more likely to be dominated by stack effect.

Stack effect and wind combine in complex fashions. The nature of the interaction is affected by the wind direction, the location of the holes in the building, and other factors.

5.3.1 Stack Effect. The stack effect is caused by temperature differences between indoors and outdoors; the result is a vertical pressure gradient inside the building. During winter conditions,

cold outdoor air enters the building through the lower portion, gets heated and rises, and exits out through the upper portion (see Figure 5-1[50]). When it is warmer outdoors than indoors, the stack effect reverses, with outdoor air coming in the upper portion of the building, cooling and falling, and leaving through the lower portion.

Some of the air passes through the walls. Outside air can also first pass through an ancillary area such as a crawl space, basement, garage, or attic. The stack effect may allow air from a tuck-under garage to enter the room above it.

The taller the building, the higher the “stack,” and therefore the stronger the stack effect. The pressure differences caused by temperature differences are greater for taller buildings. Therefore, if two buildings are equally leaky, but one is taller, the taller one will have more flow due to stack effect.

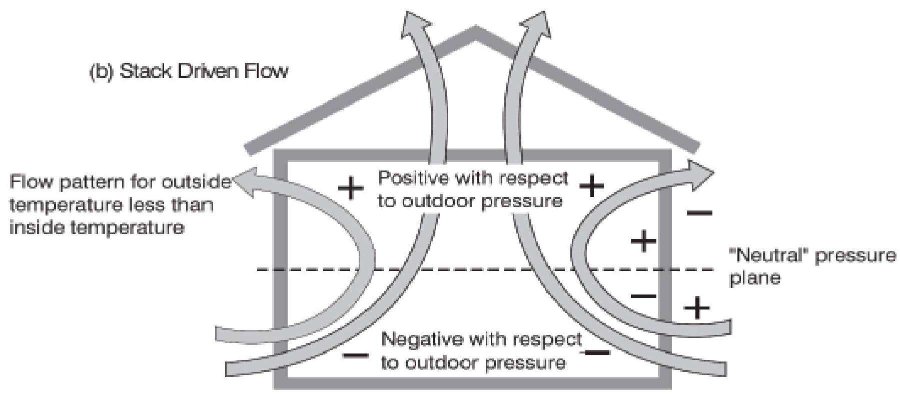

Figure 5-1 Winter-time stack effect. (By permission of the Air Infiltration and Ventilation Centre—see Reference 50.)

5.3.2 Wind. Wind-driven infiltration depends on the pressure differences generated on the outside of the dwelling by the pattern of wind flow around the dwelling. Figure 5-2[51] shows the idealized flow pattern of wind around a building in the horizontal and vertical planes. Figure 5-3[50] shows the idealized wind-driven infiltration pattern inside a dwelling. If the wind hits a building at a diagonal, two faces will have positive pressures, and the other two will have negative pressures. As the wind direction changes, the amount of wind-driven infiltration can change dramatically.

5.3.3 Combined Effect of Stack and Wind. In most dwellings, infiltration airflow is determined by the combined effects of wind and stack effect. When wind speeds are low, stack effect dominates. At high enough wind speeds, infiltration due to wind will become larger. While it is typical for the combined effect to be larger than the effect of either individually, they are not simply additive.

5.4 Induced Flow. Induced flow is often thought to be mechanically driven, as is frequently the case. Mechanical ventilation systems (exhaust, supply, or balanced) and forced-air distribution systems serve to actively move air. Additionally, during air handler operation, duct leakage to the outdoors can act as an unintentional ventilation fan. Induced flow also includes airflow due to combustion. For example, the process of drafting that occurs with a gas water heater or a fireplace removes air from and into the building in the same manner as an exhaust fan.

5.4.1 Exhaust Fans. Exhaust fans are very common, and are required by ASHRAE Standard 62.2[1] in locations such as bathrooms and kitchens. They are installed primarily for the purpose of source control, although they may also be used for whole-building ventilation.

Exhaust fans depressurize the space in which they are located. This results in an increase of air being brought into the dwelling from other locations. The air enters the home through a variety of pathways, including through walls, floors, ceilings, and from ancillary spaces, such as attics, crawlspaces, and garages. Over depressurization can result in condensation in the outer walls in humid climates in the summer where moisture levels outside the home are high. During cooling season, limiting indoor temperature to above the outdoor dew point temperature and allowing adequate drying to the inside reduces this potential.

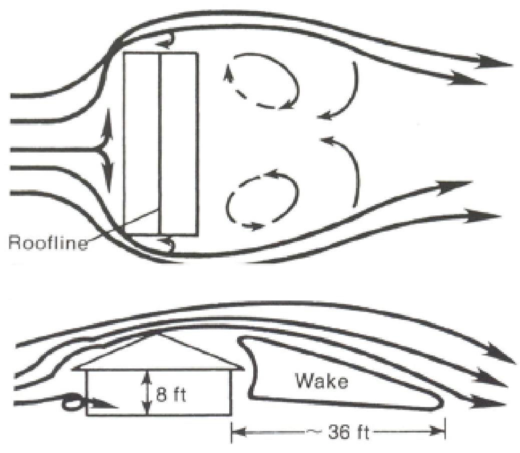

Figure 5-2 Idealized wind flow pattern around a building. (By permission of the Florida Solar Energy Center—see Reference 51.)

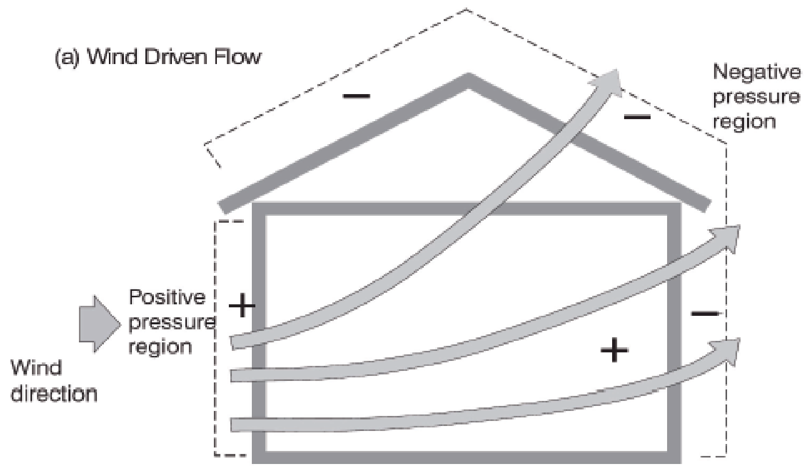

Figure 5-3 Idealized wind ventilation flow. (By permission of the Air Infiltration and Ventilation Centre—see Reference 50.)

5.4.2 Supply Systems. Supply ventilation systems are usually designed to interface with the forced-air distribution system, such that the ventilation air merges with the return air stream and is distributed throughout the home. This causes the home to be pressurized, which has the additional effect of reducing the amount of infiltration entering the home through the pathways available. Over pressurization can result in condensation in the outer walls in cold climates in the winter where moisture levels are high inside the home. During heating season, limiting indoor humidity levels reduces this potential.

5.4.3 Balanced Systems. Balanced systems, which are usually systems with air-to-air heat exchangers (heat and energy recovery ventilators); do not change the pressures in the home, assuming good connection among rooms. If individual rooms are isolated from the rest of the dwelling, there can be pressure changes, as described in the following section.

5.4.4 Forced-Air Conditioning Systems. A forced-air conditioning system does not necessarily change the pressure distribution within a home. Indeed, if the ducts are well-sealed, there is adequate return-air pathway from closed rooms or the rooms are open to one another, and there is no unbalanced ventilation system integrated with it, there should not be an impact on the pressures.

5.4.4.1 Duct Leakage. Duct leakage outside the pressure boundary (e.g., attics, garages, and vented crawl spaces) can greatly alter the pressure distribution within the home. The effect varies depending on the duct zone, whether the leakage is supply or return, and whether there is more supply leakage or return leakage.

Return leaks outside the pressure boundary draw air from the space in which the ducts are located (attic, crawlspace, garage, etc.), entraining air from this space to be distributed throughout the home. If there is more return leakage than supply leakage, the building will be pressurized, which reduces the natural infiltration into the home.

Supply leaks outside the pressure boundary lose air to the space in which they are located. This can prevent pollutants from entering these spaces from outside the space, but it forces pollutants that were already in the space into the home at a greater rate. For example, a supply duct leak in a crawl space may reduce the rate of radon migration, whereas a supply duct leak in an attached garage can increase the rate at which car exhaust enters the home.

If there is more overall supply leakage than return leakage, the building will be depressurized, which increases the rate at which air comes in from outside the pressure boundary via whatever pathways are available. Having all ductwork within the conditioned space minimizes the impact of duct leakage.

5.4.4.2 Room-to-Room Communication. Even if there is no duct leakage outside the conditioned space, there can be pressure distribution changes if individual rooms are isolated from the rest of the dwelling. This is typically the result of closed doors in homes with central returns. Closed doors do not always represent a problem if there is a sufficient undercut or some other way for air to easily move to the rest of the home, such as a return duct or transfer grille.

If there are rooms that have supply registers but are isolated from the main portion of the home where the return is located, these rooms will be pressurized, while the remainder of the home will be depressurized. This can then lessen (or eliminate) the amount of air entering the individual room as natural infiltration. Airflow from other places outside the building pressure boundary to the main portion of the home would increase.

5.4.5 Interplay of Mechanical Ventilation and Infiltration. In most dwellings, infiltration supplies outdoor air to the living space. The amount of this outdoor infiltrating air is dependent on many factors, including outdoor and indoor temperatures, wind speed, surrounding terrain, and structure geometry and shape. It is important to consider the interplay between this natural infiltration and mechanical ventilation.

If the mechanical ventilation is a balanced system, there is little, if any, interference between infiltration and ventilation; essentially, the infiltration and the balanced ventilation rates are additive. On the other hand, if the mechanical ventilation is an unbalanced supply or exhaust system, the infiltration and the ventilation rates are less than the simple sum of the two because pressure created by the unbalanced mechanical system reduces the natural infiltration. Refer to *2013 ASHRAE Handbook—Fundamentals*[96] for more detailed information.

The design of ventilation systems under *ASHRAE Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings* anticipates that the designer will take into account some of the natural air leakage (infiltration) as part of the system design and overall system sizing. Sherman evaluated how air leakage could contribute to meeting the proposed ASHRAE residential ventilation standards in new U.S. homes.[57] He found that infiltration alone is rarely sufficient to meet minimum ventilation standards. Nevertheless some amount of ventilation air is provided by these natural diving forces, and the standard allows the designer to take those into account.

5.4.6 Combustion-Induced Airflow. The proper venting of combustion products, from furnaces, water heaters, fireplaces etc., involves exhausting air via the flue. Because air is exhausted via the flue, the combustion appliance acts in a fashion similar to an exhaust fan with regard to pressure impacts on the home. Note that this is not a dynamic for appliances that do not vent, such as gas ranges and unvented gas heating appliances, or for sealed (direct-vent) combustion appliances, such as most high-efficiency gas furnaces and some water heaters/boilers.

6. OUTDOOR AIR

6.1 Introduction. This section of the guideline provides information about responding to three classes of outdoor contaminants (smog, particulate matter, and toxins), depending on the type of contaminant source and the conditions of the dwelling.

6.2 Outdoor Air Acceptability. *ASHRAE Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*[1] assumes that the outdoor air is acceptable. The designer is encouraged to ensure this assumption is correct in the design of a particular ventilation system. Nevertheless the infiltration of outside air is assumed to provide improved IAQ and is acceptable as a part of the ventilation strategy envisioned by the standard.

When outdoor air is not acceptable, special actions should be taken to maintain acceptable IAQ. At a minimum, outdoor air is required to meet standards for ambient air established by the cognizant authorities. The U.S. EPA has established National Ambient Air Quality Standards (NAAQS), see Table 4.1). *ASHRAE Standard 62.2, Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings*[1] defines acceptable indoor air as “air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be contaminants at concentrations that are known to pose a health risk.” This is also a necessary requirement for acceptable outdoor air that is going to be used for residential ventilation. As such, outdoor air should not only meet the NAAQS, but also be substantially free of the contaminants that ventilation air is intended to dilute.

6.3 Migration of Outdoor Pollutants to Inside. The outdoor air pollutants of concern in the indoor environment include components of smog (NO_x, SO_x, and ozone), particulate matter (dust, allergens, molds), and toxins (accidental or intentional releases). In some cases, outdoor air quality can be unacceptable for extended periods of time (e.g., smog in some urban areas). In other cases the unacceptable outdoor air quality may be routine but occasional (e.g., air from feedlots, paper mills, or lead smelters). Poor or dangerous outdoor air quality can also arise from unusual events such as wildfires or accidental releases of toxic substances, such as from chemical spills.

Emmerich and Persily used CONTAM[52] to model the impact of some outdoor air pollutants (CO, NO_2, and coarse particulate matter) on IAQ in typical and tight construction homes in Minneapolis and Miami.[53] They modeled elevated outdoor pollutant emissions and the corresponding indoor concentrations, taking into account hourly emission patterns and the operation of a standard furnace or central cooling system. The outdoor emission rates modeled

varied by time of day and ranged from 4 to 12 ppm CO, 200 to 400 ppb NO_2, and 75 µg /m^3 coarse particles. The resulting average indoor concentrations were as follows: 6.8 ppm CO, 66 ppb NO_2, and 11 µg /m^3 coarse particles. This study demonstrated that indoor concentration of pollutants can be significantly lower than outdoor.

Thatcher and Layton examined the outdoor and indoor particle concentrations in a dwelling in Livermore, California.[54] The particles found in their study dwelling were predominantly larger coarse particles (5 to 25 microns, 83 percent of the total dust mass). While previous studies concluded that the building shell served to filter particles out of the infiltrating air, Thatcher and Layton found this was not true if deposition factors were taken into account. They found the main differences between outdoor and indoor particle concentrations were due to different deposition velocities (the rates at which particles deposit on a surface) for given particle sizes. Smaller particles have lower deposition velocities, so their indoor concentrations are not reduced as much due to settling. Coarse particles, greater than 10 microns in diameter, are often visible and settle out of the air quite easily. Activity has an impact on the level of resuspended particles greater than 5 microns while submicron particles are not affected by household activities such as cleaning or walking.

6.4 Mitigation Strategies. Based on how fans and natural forces remove indoor air pollutants from a dwelling, there are four basic strategies that can be used separately or in combination to reduce occupant exposure to contaminants in outdoor air:

- shelter in place
- building air tightening and pressure management
- ventilation and air filtration
- contaminant removal

The ability to respond with any of these options will depend on the design of the home, its mechanical systems, and the types of pollutants present and their release and exposure patterns (short-term, cyclical, seasonal, long-term). An effective approach to reducing exposure to outdoor contaminants will typically require a combination of the four strategies, but even with a combined approach there may still be some periods in which the IAQ is still unacceptable.

6.4.1 Shelter in Place. The most fundamental function of a home is to provide shelter from outdoor conditions. It is intended to be the first line of defense at separating the relatively uncontrolled outdoor environment from the desired indoor environment. The first response of many people to poor outdoor air quality is to go inside and close the windows. Additionally, they could turn off their central heating and air conditioning systems and any other ventilation fans. Closing windows (and other air intakes) will reduce the air exchange with the outdoors and therefore the immediate intrusion of outdoor air into the home. However, this would also potentially increase contaminants that are generated inside the dwelling, such as particulate matter and combustion by-products from cooking.

Except for reactive gases such as ozone, the building envelope serves to delay, not necessarily reduce, the introduction of outdoor contaminants into the indoor environment. Such a delay is not very helpful at reducing exposures to outdoor contaminants that persist over days, but can be

an effective strategy for short-duration sources. The delay time, or the amount of time it takes to completely change the air in a building, is determined by the ventilation rate. The effectiveness of sheltering within the home will thus depend on the envelope tightness. For a home with an air change rate of 0.35 air changes per hour, the average delay time is roughly three hours.[47] For a tight dwelling without mechanical ventilation, the delay time can easily be twice as long. However, many existing dwellings in the United States are leaky (i.e., typically one air change per hour) and thus could have a much shorter delay time on the order of one hour. After the outdoor contaminant is gone, windows can be opened to flush out the pollutants that entered during the exposure period.

6.4.1.1 Safe Havens. Simply going inside may not be sufficient for the highly unusual, but potentially lethal, events associated with forest fires, chemical spills or fires, explosions, bio-terrorism, or similar toxic releases. These events can temporarily create clouds of outdoor air so noxious as to make all other air quality issues pale in comparison. When sufficient warning is provided, occupants are often advised to leave the vicinity, but the unexpected nature of these events means that the only viable alternative may be to shelter in place.

Because homes, as a whole, may be too leaky to provide the level of protection needed, individual rooms within a home can be temporarily sealed up to become safe havens. A safe haven should have as little contact with outside walls as possible and preferably be on the side of the dwelling furthest downwind from the source. Duct tape can be used to seal leaks, cracks, seams, and doors, with thick plastic sheeting used to span larger gaps.[55] For at-risk individuals or in locations where an event is more likely to occur (e.g., near a chemical plant), a safe haven can be constructed in advance with a small, but highly efficient particle and gas-phase filtration system capable of providing several hours of protection. This could be effectively combined with other emergency shelters (e.g., tornado or hurricane) to reduce cost.

An additional example of a safe haven is one created for everyday use by susceptible individuals to provide acceptable IAQ in one room of a dwelling (typically a bedroom) that provides protection from other indoor sources of contaminants, which might have far greater impact on inhabitants than outdoor sources. Such a safe haven includes rigorous source control including ceramic floors, careful selection of low-emitting building materials, furnishings, cleaning products, personal care products, etc. Additionally, these safe-haven rooms are often pressurized with respect to other rooms and the outdoors, using HEPA and carbon filtered air.

6.4.2 Building Air Tightness and Pressure Management. Sheltering in place is an example of a barrier strategy intended to keep the contaminated air out and can be effective in critical situations. Designing the building and its systems to control the flow of air, however, can have more general applications. Careful design of the building envelope and attention to pressure management can sufficiently control flows in and out of a dwelling to acceptably retard exposure in many instances.

6.4.2.1 Building Air Tightness. The construction of the building envelope (windows, doors, walls, ceiling/roof, and floors) and its corresponding air tightness level dictates how long the dwelling is able to delay outdoor air pollutants from entering the building, as well as how fast the air in the dwelling is replaced with outdoor air to purge indoor contaminants, whether from

indoor sources or from short-term outdoor pollutant exposures. The strategy of "build it tight—ventilate it right" offers a significant advantage when the outdoor air is unacceptable. Sherman and Matson have demonstrated that U.S. new construction is significantly tighter than the stock as a whole (normalized leakage values of less than 0.50 for new construction compared to twice that for the existing housing stock).[56] Sherman evaluated how air leakage could contribute to meeting the proposed ASHRAE residential ventilation standards in new U.S. homes.[57] He found that air leakage alone is rarely sufficient to meet minimum ventilation standards.

Existing U.S. dwellings can be quite leaky as a whole (average normalized leakage values of 1.03).[58] In terms of mitigation strategies, air-tightening techniques (caulking and sealing cracks and holes in the building envelope and interstitial spaces, and space-conditioning air duct sealing) can reduce the amount of infiltration and, correspondingly, the ingress of outdoor pollutants. Studies have found that these basic techniques, applied properly, can reduce the normalized leakage values of existing dwellings by about 25 percent.[59] This increases the delay time by a similar fraction. More aggressive techniques can be used to reduce the leakage even further.

6.4.2.2 Pressure Management. Pressure management strategies can be used in situations with unacceptable outdoor air quality to maximize the exposure of the occupants to relatively clean indoor air and to minimize their exposure to the contaminated outdoor air. Houses are subject to natural pressures created by the wind and indoor-outdoor temperature differences.

Short of rather extreme architectural changes, there is not much that can be done to change these natural pressures, but there are other pressures and flows induced by building systems that are more controllable. Pressure management includes controlling exhaust devices (flues, chimneys, and exhaust fans) and air moving devices (air distribution systems, air cleaners, and ventilation systems). Just as proper management of these systems can provide additional protection from outdoor contamination, improper management can negate the benefits of the other strategies.

When a central air handler operates, it tends to equalize the concentration of contaminants among indoor spaces by recirculation mixing. For example, contaminant concentration may spike in a bedroom with two people overnight, while large unoccupied areas of the home may have low concentration. Recirculation mixing lowers the exposure in the smaller high concentration area a lot while raising the overall average concentration in the house a little.

Central air handlers can also increase the amount of outdoor air that enters the home by differentially pressurizing certain rooms, by having leaky ducts outside the conditioned space, or by having intentional outdoor air inlets as part of the ventilation system. In all these cases, running the air handler will increase exposure to outdoor contaminants by increasing air exchange. To maximize the value of sheltering, pressure management techniques (air duct sealing and balancing supply and return airflows between rooms) should be used to minimize the pressure difference across the envelope and lower the amount of air that comes into the home.

For short-duration outdoor air contamination events, it is best to shut off most air moving equipment, including exhaust fans and other ventilation systems as well as the central air handler. If the outdoor contamination is mild, or of sufficient duration, the occupants may wish

to run the central air handler, but not exhaust or supply fans, either to dilute indoor sources or to provide thermal comfort. In such cases the pressure imbalances should still be minimized as much as possible by, for example, leaving internal doors open.

Air supply pressure management can make any available filtration more effective, especially if large openings (doors and windows) are closed and outdoor air is directed through available filtration before mixing with the indoor air. If no active filtration is available, ventilation systems and fans should be disabled to allow infiltrating air to take advantage of whatever gas-phase filtration is achieved through the building envelope.

6.4.3 Ventilation and Air Filtration. Ordinarily, outdoor air is presumed to be of better quality than indoor air. As such, natural and mechanical ventilation systems transport outdoor air into a dwelling to dilute indoor contaminants. Operated during times of poor outdoor air quality, they can also bring outdoor pollutants inside and degrade IAQ. Even so, ventilation systems that draw ducted outdoor air and include filtration and air cleaning capabilities can be useful for diluting pollutants and contaminants in the indoor environment. The type of system installed and used will depend on the types of pollutants most likely to be present. This section describes the various types of ventilation and filtration systems and their applicability to different pollutants.

Going indoors to escape from poor outdoor air quality may be a good solution when the period of high outdoor concentration is short, but when the outdoor contamination extends over a longer period of time, filtration (including air cleaning) may be the only option to reduce indoor levels of outdoor contaminants. It would be ideal to remove the contaminants in outdoor air before they mix with the indoor air, but this is possible only if all the sources of incoming air are controlled. In such a case, filtration could be applied to the incoming air stream, provided the single-pass efficiency of the filter is high enough. Filtration to control indoor sources is a separate function, but when efficient filtration of the entire outdoor air stream is not possible, recirculation filtration of the indoor air may be a workable alternative. Recirculating filtration can be done on a room-by-room basis, with a dedicated system, or as part of the whole-house air distribution system.

ASHRAE Standard 52.2, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size[60] specifies rating values for particulate filters. Particle filters with minimum efficiency reporting value (MERV) ratings below 6 are poor at filtering out respirable particulates (typically below 2.5 microns), but can do an acceptable job at removing the large visible particles such as fibers, insects, or large dusts or pollens (typically above 10 microns).

Recent research by Logue et al[31] suggests that mass of particles below 2.5 microns ($PM_{2.5}$) may be one of the most significant indoor airborne contaminants in terms of chronic health impact in residences of those that have been well studied. $PM_{2.5}$ is also the most straightforward contaminant to remove from indoor environments through filtration. MERV 10 rated filters and higher are preferred for removing smaller airborne allergens and $PM_{2.5}$ particles.

Primary sources of ultrafine (<0.1 micron) particles (UFPs) in homes are from outdoor sources (primarily automobile exhaust) and from electric or gas-stoves as well as other combustion sources (unvented fireplaces or candles). Rim et al[32] provides a quick review of health effects

(increased respiratory and cardiovascular mortality; inflammation of lung cells; etc.), and information on how the use of kitchen exhaust hoods can significantly reduce UFP levels in homes. Without directly exhausting stoves to the outside, indoor UPF levels can be 10 times higher than outdoor levels during cooking. While UFPs, typically measured as the number of particles in 1 cm^3 of air are a subset of $PM_{2.5}$, they are not well characterized by mass and do not correlate well with $PM_{2.5}$ measures due to their small size and small mass. While additional study is required before the risk from UFPs is as well characterized as that from $PM_{2.5}$, UFPs have been shown to be a risk factor in indoor air quality and reducing their number will reduce risk. Hoek et.al.[109] report a median all-cause mortality effect size for UFP of 0.3% associated with an increase of 1,000 particles/cm3 and compare that to a 0.6% effect size of $PM_{2.5}$ with an increase of 1 $\mu g/m^3$.

In addition to point-source exhaust ventilation of cooking, to further reduce UFPs higher-efficiency (MERV 13 and higher) filters should be considered.

Multistage particle filtration (a relatively coarse filter followed by a high-efficiency filter) can help filter out different sized particles without overloading the higher-efficiency filters. When selecting filters, consideration should be given to the effects of the filter's pressure drop on delivered air flow, fan capacity, and energy use.

6.4.4 Contaminant Removal. Sometimes simple hygiene measures can provide protection. Because coarser particles can settle on surfaces and be resuspended later, cleaning and vacuuming may be needed to remove the particles. Care should be taken to assure that the vacuum system used actually removes the particles and does not merely resuspend and recirculate them. Central vacuum systems with outside exhaust are best for this purpose, but many vacuum cleaners now have secondary filtration (typically HEPA) that can trap smaller particles.

6.4.5 Combined Strategies. Table 6-1 summarizes the combination of strategies to consider when trying to reduce indoor exposures to specific outdoor pollutants. Preventive air tightening, correction of pressure imbalances, the implementation of appropriate filtration and ventilation measures, and evaluating the feasibility of a safe shelter-in-place zone (if needed) will help reduce the impact of outdoor pollutants on the indoor environment. Putting all these mitigation strategies together in a well-engineered system can help to protect occupants from contaminants in outdoor air. In addition to good system design, the occupants need to manage the system correctly.

TABLE 6-1 Ventilation, Filtration, and Contaminant Removal Strategies for Reducing Indoor Exposures to Outdoor Pollutants

Contaminant	Sheltering in Place	Building Air Tightening and Pressure Balancing	Ventilation (if insufficient infiltration)	Filtration	Contaminant Removal

Allergens	Yes	Yes	Supply ventilation with filtration (better) Or Exhaust ventilation	MERV 6-8 (minimum) MERV 10-13+ (better) Or Stand-alone high efficiency particle filtration system	Cleaning and vacuuming (high efficiency particle filtered)
Soot and Other Particulate Matter	Yes	Yes	Supply ventilation with filtration (better) Or Exhaust ventilation	MERV 13 or higher efficiency filter if soot includes ultrafine particles	Cleaning and vacuuming (high efficiency particle filtered)
Gaseous Contaminants	Yes	Yes	Supply ventilation with filtration	Gas phase filtration (charcoal absorption)*	Reduce outdoor emissions
Toxins	Yes	Yes	Shelter in Place and turn off central distribution system to minimize toxin circulation into safe haven. At-risk individuals may need to create a safe haven with high-efficiency particle filtration and gas-phase filtration	Gas phase filtration (charcoal absorption) if the contaminant to be removed is known	Reduce outdoor emissions

*If no gas-phase filtration in place, circulate air within the dwelling to lower ozone concentration by decomposition and shelter in place during high ozone periods.

7. MOISTURE

7.1 Introduction. Moisture is a common problem in homes and can have serious consequences, including mold growth, deterioration of building materials, and providing a suitable environment for pests. In humid climates, additional moisture can result in greater energy use by air-conditioning or dehumidifying equipment.

However, moisture is not always a pollutant in the way many other substances are. Many substances, such as particulate matter and gases such as CO and VOCs, are always considered to be pollutants because it is always better to have less of these substances. For moisture, however, if too much is removed from the air, then the air becomes too dry for comfort and good health. This often happens with excessive infiltration or mechanical ventilation in cold climates during the winter months.

As a result, ventilation is not always necessary for humidity control, since the humidity levels are frequently satisfactory without any active control. When mechanical ventilation is part of the moisture-control strategy, there are many factors to consider, including placement of ventilation, fan airflow rates, outdoor dew point temperatures, and interior moisture sources.

For mold growth to occur, the relative humidity must be at least 70–80% at the surface, with many mold species requiring higher levels. The moisture content of materials is a key element of assessing the risk of microbial growth on their surfaces.[104] Microbial growth, including mold and bacteria, does not occur without an accumulation of excessive amounts of moisture for a sufficient amount of time, within an adequate temperature range and in a material or surface

coating that is microbially digestible.[104,105] Mold growth can also occur if there are plumbing or envelope leaks, regardless of the indoor relative humidity.

Because cold surfaces can result in condensation of moisture within this relative humidity range, 70 percent relative humidity cannot be considered an upper threshold for healthy room air humidity levels. For example, a home with 50 percent relative humidity and an indoor temperature of 70°F will produce condensation on standard double-pane windows when the outdoor temperature is about 10°F.

7.2 Moisture Balance. The moisture balance is essentially the difference between the moisture within the home and the moisture in the air outside the home. This mass balance is expressed in terms of absolute or specific humidity (vapor pressure), rather than relative humidity.

In the absence of mechanical dehumidification, the moisture balance will, on average, determine the amount of moisture generation within the home. At any given time, however, the moisture balance may be higher or lower than would be expected simply due to generation alone. This is the result of buffering, where hygroscopic materials within the building absorb and release moisture. As a result of internal moisture generation and buffering, the absolute humidity in the indoor air will not fluctuate as greatly as that of the outdoor air.

7.3 Increased Moisture in Buildings. Excessive moisture in buildings can be classified into two general types: bulk moisture and water vapor contained in the indoor air.

7.3.1 Bulk Moisture. Bulk moisture is a concentration of liquid water typically resulting from a leak. The leak is most often a plumbing leak or a leak in the envelope through which rain water or melted snow or melted ice can enter. Damage is typically located at the site of the leak or along a direct path from the leak, such as directly beneath the leak or following the flow of water along paths such as wiring, pipes, etc.

7.3.2 Elevated Indoor Humidity. Elevated indoor humidity often results from the evaporation of indoor moisture, such as from drying clothes, fuel-wood storage, unvented combustion, cooking, showering, and respiration by the occupants. Overcrowding in homes can be a major contributor to elevated indoor humidity. If the humidity results in damage such as mold growth, it may be found virtually anywhere in the building, at any distance from the original source of the moisture, usually where there is a cooler surface which facilitates condensation on non-hygroscopic surfaces and sufficient levels of bound water within hygroscopic materials.

Elevated indoor humidity can also be caused when infiltration or ventilation brings in air that contains more water vapor than the indoor air. In the absence of moisture removal by mechanical systems, indoor humidity may rise to unacceptable levels.

ASHRAE Standard 160-2009, *Criteria for Moisture-Control design Analysis in Buildings*[105], specifies design criteria for indoor design relative humidity for room air to reduce moisture damage based on climate and HVAC system operation. It provides three methods of determining what humidity should be used.

7.4 Ventilation and Moisture. In regard to the degradation of buildings, bulk moisture from leaks is often the more catastrophic of the two general types of excessive moisture. This is best addressed by fixing the leak and drying the water damaged materials within 48 hours. If more than 48 hours elapses between the water damage and complete drying, materials may need to be discarded and replaced.[110]

Exhaust ventilation is useful in lowering humidity levels in homes, when used at the source of moisture generation, such as in bathrooms and kitchens. By exhausting the moisture from the source directly to the outdoors, the moisture does not have a chance to migrate throughout the home.

For whole-building ventilation to be effective at lowering indoor humidity, the outdoor ventilation air must have a lower absolute humidity (dew point) than the indoor air.

7.5 Locating Local Exhaust Ventilation for Moisture Control. The most important place to locate exhaust ventilation for effective moisture control is in rooms where moisture is generated. These rooms include bathrooms, primarily those with showers; kitchens; and laundry rooms. To be most effective, the exhaust fans should be properly ducted all the way through the envelope to the outside. If they are not properly ducted to the outdoors, the moisture might find its way back into the home; it can also cause damage to the building spaces in which it is deposited.

7.6 Additional Effects of Ventilation on Moisture Levels

7.6.1 Ventilating for General Pollutant Control. Although whole-building ventilation may not always be beneficial for controlling indoor humidity levels, it is still essential for controlling other pollutants and odors. Increasing or decreasing ventilation rates will affect indoor humidity levels, sometimes resulting in humidity levels that are too high or low. Additionally, many homes have the potential for moisture problems during some part of the year regardless of ventilation system operation. In this case, additional mechanisms may be required to return the humidity levels to acceptable levels. Possibilities for this type of control can include humidifiers, dehumidifiers, and increased use of air conditioners. This does, of course, come with an associated energy cost, so it is important to use energy-efficient options to minimize the cost associated with the dilution of general pollutants.

7.6.2 Ventilation in Humid Climates. Ventilation in humid climates has the potential to increase the moisture (latent) load addressed by the air-conditioning system. Therefore, whole-building ventilation should be kept to a minimum in these areas, with enough ventilation, as defined by ASHRAE 62.2[1], provided for the dilution of other pollutants and odor control. Local exhaust ventilation should still be provided for source control in high-moisture rooms of the home.

7.7 Humidity Control Options. Two major types of active humidity control options currently exist: vapor compression dehumidifiers; and desiccant dehumidifiers. Vapor compression dehumidifiers or desiccant systems can be stand-alone systems or integrated with the central air distribution system to provide dried ventilation air from outdoors or to dehumidify recirculated indoor air directly. Desiccant systems can also include heat recovery options to increase overall

energy efficiency. The cost effectiveness of each option depends on the desired control level, relative energy costs, ventilation rate, and humidity load.

When humidity is directly regulated by a humidistat-controlled vapor compression system or desiccant dehumidifier, there is some indication that occupants will be comfortable at a higher sensible space temperature, which may increase emission rates of formaldehyde and other VOCs. By properly designing the overall system, increases in energy consumption while using a dehumidification system are minimized. Controlling humidity reduces the risks of mold growth and also helps control other indoor contaminants such as dust mites.

7.7.1 Vapor Compression Dehumidifiers. Vapor compression dehumidifiers put both the condenser and evaporator in the same airstream, with a fan in the middle. The process air passes over the evaporator coil and is cooled below the dew point. Moisture in the airstream condenses on the cold coil and drains off to collect in a pan or to a drain line. The cooled air then passes over the condensing coil, where the cool air is warmed. The net effect on the process air is increased air temperature and reduced humidity.

Systems which collect condensate in a drain pan need to be periodically emptied by the occupant. A system which is installed with a drain line connected to a floor drain or sump does not need to be attended to by the occupant, and may be used more regularly by the occupants.

7.7.2 Desiccant Dehumidifiers. Desiccant systems are installed as part of the HVAC system, and a dry desiccant system, for example, uses a honeycomb wheel coated with a hygroscopic material. The wheel rotates between a moist process airstream and a regeneration airstream. As the process air passes through the wheel, the desiccant material adsorbs water from the airstream. The temperature of the process air increases and the humidity ratio (or, alternatively, dew point) is decreased. On the regeneration side of the wheel, return air or outdoor air is heated, by an electric heater or gas burner. As this hot air passes over the wheel, the water adsorbed on the wheel is released into the hot air, which is then discharged to the outdoors. The system is controlled by a humidistat which cycles operation to maintain the desired humidity level. Liquid desiccant systems use a spray of liquid hygroscopic material instead of a wheel.

8. CONTAMINANT GENERATION AND TRANSPORT

8.1 Introduction. At the time of exposure, contaminants are part of the air we breathe. The pathway between release from a source and inhalation can vary: a particular contaminant might have been transported by water or hitch-hiked a ride on animals or the occupants themselves. Contaminants may be released outdoors and transported into dwellings as part of the ventilating air or carried in and resuspended from clothing, a pet's fur, or from the floor. Contaminants may also be released directly into the indoor air. This section examines some of the common patterns of sources and transport mechanisms.

8.2 Built-in Contaminants. The source of some indoor air contaminants is the materials that form the structure or finishes of the building itself. The contaminants may be gases or particles. Gases are released from adhesives and finishes applied in factories or at the site during construction or from a material itself. Gaseous release occurs by two distinct mechanisms—

evaporative release (the primary mechanism) and diffusion release (a secondary mechanism). When adhesives or finishes are wet, there is a short-term burst of compounds released, usually from those that form the carrier for the bonding agent or finish materials.

For manufactured items, this release occurs at the factory. After the materials have dried, gases must migrate through the products by diffusion to be released into the air. This proceeds at much slower rates than evaporation. Some manufacturers plan the production process to maximize the amount of contaminant released at the factory. Examples are composite materials such as particle board, medium density fiberboard, oriented strand board, cellulose ceiling tile, and plywood, which are made of wood and adhesives that may release various volatile and semi-volatile compounds. Because the constituents of glues and adhesives and manufactured materials are continually changing in response to price, availability, regulation, and consumer demand, only ongoing testing can provide the information needed to guide the selection of products. Fiberglass and mineral fiber products may release fibers into the air when improperly installed, physically disturbed, or damaged by water.

The half-life of volatile compounds may be months or years, depending on the compound. In addition, higher temperatures and absolute humidity levels may increase the rate of release. In some cases, chemical reactions may occur that create contaminants that were originally not part of the product. For example, some composite materials with something slightly wrong in the chemistry, when exposed to high temperature and humidity, may produce odors described as smelling like vomit, fish, or old socks. In these cases the product may be in place in the building for some time before the problem begins. Information about compound outgassing is not available on a systematic basis. In addition to gaseous contaminants, the moisture and microbial dynamics of composite materials derived from plant fibers can affect IAQ.

Some adhesives are applied on site rather than in factories. In these cases the emissions from the wet state are released into the building. Site-applied adhesives are used to adhere textile and sheet floor coverings and to adhere laminates on cabinetry and roofing materials. They are also used to attach gypsum board to studs. Many construction adhesives contain compounds that may outgas. Over the last decade, low VOC products have been introduced into the marketplace. The low VOC products are usually not free of harmful chemicals, but they offer an improvement in the amount of VOCs released.

Varnishes and paints may be applied at the factory or at the site. Although factory-applied products have the advantage of releasing the evaporative contaminants at the factory, some products are still significant emitters after curing. Research performed in California found that acid-cured polyurethane finishes on cabinets released formaldehyde at the same rate as the medium density fiberboard forming the carcass of the cabinets.[61] Low-emission paints and varnishes are readily available. However, it is wise to consider the performance characteristics of the product. Painting with a low-emission product three times over the course of five years may release more contaminants than painting once with a more durable product with higher initial emissions. Durability specification should be a part of the selection process.

Floor coverings fall into two distinct categories—hard surface flooring and textile flooring. Both hard surface and textile floor systems can release volatile compounds. Floor coverings should be

thought of in terms of assemblies. The covering itself often rests on a substrate that may itself release contaminants. Carpet may be installed on a carpet cushion, ceramic tile on a fiber reinforced cement board, and vinyl on laminated wooden subfloors covered by a leveling compound. Wooden floors are often installed on a layer of rosin or felt paper. Carpet, wooden, laminate, and vinyl floorings may be glued to the substrate, introducing a wet applied product into the system. Ceramic tile is always adhered using modified mortar. Some of the products used in flooring systems outgas contaminants. As with other products, manufacturers have made efforts to reduce emissions from flooring system components. The Carpet and Rug Institute (CRI) has developed maximum emission guidance for carpet, carpet cushion, and adhesive. By allowing outgassing of contaminants during the manufacturing process, some manufacturers are able to deliver products that release a small fraction of the CRI guidelines. These products use integrated carpet cushion and pre-applied adhesives. In addition to releasing volatile compounds, flooring products can affect IAQ by their impact on particle dynamics and properties when applied to concrete that is damp with construction water or from poorly managed rainwater.

8.3 Tracked-in Contaminants. Many particles are tracked-in on people's feet or carried in attached to clothing or other objects. The particles become air contaminants if they are re-suspended in the indoor air. The chances of resuspension and exposure depend on the size of the particles, where they are deposited, and how they are disturbed. For example, large particles, greater than 5 to 10 microns, settle quickly to horizontal surfaces, so in order for them to cause an inhalation exposure, they must become airborne close to the occupant (they may also remain on horizontal surfaces and become a dermal or hand-to-mucous membrane exposure). Smaller particles, those in the one-to-five micron range, stay airborne longer. Submicron particles begin to exhibit the characteristics of gases, being influenced as much by collisions with molecules and other particles as by gravity.

Resuspension dynamics are also affected by the characteristics of the surface to which they have attached. Hard surfaces like ceramic tile, laminate, wood, or plaster are less able to store particles. It is relatively easy to resuspend particles from them. Textile materials have a great deal more surface area to which particles may attach. When the textile is relatively clean, this is an advantage. Clean textiles collect airborne particles and sequester them. Textile coverings that harbor many particles may reach a point where they become virtual sources of airborne particles. In a study of school classrooms with hard-surfaced and textile floor coverings, airborne particle levels were 30 percent higher in rooms with carpeted floors than in rooms with hard-surface floors.[62] The occupancy, ventilation rates, and filtration were the same for all rooms. This study provides evidence that particles that have settled can be resuspended in the air. Settled dust in buildings contains heavy metals[63], pesticides[64], and fungal spores.[65] Allergens from pets and pests can also be stored and then resuspended. Health issues associated with carpets have been reviewed elsewhere.[117]

8.4 Colonization of Biological Contaminants. Buildings suitable for occupancy by people may also contain ecological niches for nonhuman organisms. All creatures need food, water, shelter (from adverse climate and other creatures), and a place amenable to reproduction. Buildings consist of many cavities that go largely unobserved, providing first-rate shelter for mold, insects, small mammals, and cavity-nesting birds. Water is provided in the form of rainwater, plumbing leaks, condensation, or groundwater. Food needs vary from creature to creature. The creatures

that cause the most damage are those that colonize buildings in social groups. Insects, rodents, and bats are the main colonizers. To control colonization of buildings in the long run, the carrying capacity of the building must be lowered by addressing food, shelter, water, and migration routes. While supplemental pesticides may be required in some circumstances, it is not possible to control pest species by pesticide use alone.[66] Intimate knowledge of the pest species behavior in finding food, water, shelter, and a mate are crucial to effective control. The ASHRAE Indoor Air Quality Guide, which can be downloaded free, provides detailed information on how to design and build to exclude pests and the use of integrated pest management[111].

8.4.1 Moisture and Biological Contaminants. Moisture is not, strictly speaking, a contaminant, but it is a prerequisite for colonization by molds, many insects, and rodents. In addition, epidemiological studies link dampness in buildings to respiratory symptoms like coughing and wheezing.[67]

8.4.2 Mold. Mold is a microscopic fungus consisting of thread-like hyphae and fruiting bodies that produce spores, the origin of the next generation. Molds are primary decomposers, digesting the remains of plants and animals largely by aerobic decomposition. Spores from molds that commonly grow indoors are in the 2 to 10 micron range. Outdoor air in most locations in the United States contains many airborne spores throughout the year, except during seasons too cold to support active mold growth. Although many spores enter buildings with infiltrating air or are tracked in on feet, nearly all materials that enter a building have mold spores attached to their surfaces.[68] Moisture levels are the primary factor determining mold growth in buildings. Investigation, remediation, and prevention all focus on moisture dynamics in buildings.

Mold needs a carbon source for nutrients, water, temperatures between 45°F (7°C) and 100°F (38°C), and oxygen. It needs a place sheltered from sunlight. There are many places in buildings that provide these needs, especially in the foundation area where there is increased risk of rainwater and groundwater entry, plumbing leaks, and condensation.

8.4.3 Insects. Insects may colonize buildings or simply be passing through. Although many genera colonize buildings, it is the social insects that cause the most problems. Carpenter ants, termites, fleas, carpet beetles, roaches, yellow-jackets, white-face hornets, honeybees, and moths can cause injury to occupants, food, or the building itself. Solitary wasps and bees that may also colonize buildings are generally few in number and impact. Mosquitoes, although they only infrequently colonize a building, may transmit infectious diseases and often colonize the surrounding landscape.

8.4.4 Dust Mites. There are tens of thousands of species of mites. The one most often linked to indoor air problems are dust mites. Dust mites colonize humidified, porous materials in buildings. In climates where the indoor relative humidity is greater than 55 percent for an extended portion of the year, dust mites may inhabit large areas of carpet and furnishings. In climates where the indoor humidity is less than 55 percent for extended portions of the year, dust mite colonization recedes to inhabit humidified microclimates. Bedding, frequently used stuffed chairs, and stuffed animals are humidified by the people who use them. Textile floorings placed on concrete at or below grade may be humidified by water transported through the concrete from

below. Washing bedding and textiles in water above 132°F (55°C) will kill dust mites. If wash water of this temperature is not available, drying the material in direct sunlight will usually kill the mites.

8.4.5 Rodents. Although there are many species that have suffered huge population losses as the result of human activities, rats and mice have thrived. The rodents who colonize buildings are burrowers and climbers. A sewer pipe or drain line provides an inviting entry into a building. As long as we bury pipes under our buildings and flush nutrient down them, we will have a large rodent population beneath our buildings. Some rodents are disease vectors. They are all unsanitary and may cause damage to buildings as well.

8.4.6 Bats. Bats are drawn to dark cavities with consistent temperature. They frequently move into attics, garages, sheds, and barns. Populations in residential buildings may range from one or two to a few dozen. Although they are associated with rabies, there are very few cases of rabies being transmitted to humans from bats. Large deposits of guano may be contaminated by fungi that are opportunistic pathogens in humans. Bats are predators that consume huge quantities of mosquitoes and moths.

8.4.7 Birds. A number of bird species often colonize buildings. Starlings, pigeons, and English sparrows can all become nuisances in buildings. As with bats, the major source of hazard is from fungi that may grow in accumulated droppings.

8.5 On-Site Pollutants. Some pollutants in the home originate on-site but not as part of building materials. These come primarily from the storage or use of consumer products such as paints, cleaners, fragranced personal care products, or from soil gases such as radon.

8.5.1 Storage and Use of Consumer Products. Many consumer products, such as paints, cleaners, pesticides, solvents, and fragranced personal care products can emit pollutants into the home. These primarily take the form of volatile organic compounds and are usually gaseous. Some research has suggested that combinations of certain gases can produce particles.[69] When these products are used in the home it is advisable to substantially increase ventilation over normal levels by opening doors and windows and by operating exhaust fans.

When not being used, these products are often stored in basements, attached garages, or in the main living space itself. Even when stored, these products continue to emit pollutants that can lead to elevated exposures in the home. For example, one study of 15 residential garages found many potential contaminant sources, including automobiles, lawn mowers, fuel in containers, paints, solvents, woodworking supplies, lawn care products, and oil spills.[70] It is recommended that these products be stored outside of the home or any attached unconditioned spaces. Additional protection of occupants can be achieved by providing continuous ventilation of attached garages with proper protection against back-drafting any products of combustion from gas appliances in the garage.

8.5.2 Radon. Radon is a radioactive gas that is part of the radium decay series and is related to increased risk of lung cancer. There is evidence that the increased risk is greater for smokers than for non-smokers. It is released into the air between soil particles and cracks and fissures in rock.

It enters buildings primarily with air that passes through underlying soil and rock before entering the building. Radon studies in residential buildings in the 1980s found that radon levels in crawl spaces were almost double those found on the first floor.[71] Guidelines for new residential construction are required in some jurisdictions where radon concentrations can be high.[72]

8.6 Combustion Appliances

8.6.1 Combustion Basics

8.6.1.1 Hydrocarbon Fuels. Combustion equipment burns some form of hydrocarbon fuel. Hydrocarbon fuels all consist of a string of carbon atoms, each of which is bonded to additional carbon and hydrogen atoms. Methane, the primary constituent of natural gas, is the simplest form, with a single carbon atom and four hydrogen atoms, CH_4. Other gases, such as ethane, propane, and butane, have more carbon and hydrogen atoms (C_2H_6, C_3H_8, and C_4H_{10}, respectively). As more carbon atoms are added to the molecules, more complex formations of the carbon atoms can occur. Forms with long strings occur as liquids such as kerosene, gasoline, and fuel oil; or as solids such as wood or coal. Liquid or solid fuels are mixtures of many different hydrocarbon molecules.

All fuels have impurities. Distilled fuels have the fewest impurities. Gases, by their nature, are highly distilled and have the fewest impurities. Distilled liquids like gasoline have fewer impurities than liquids such as residual oil and solids such as coal. Many impurities will result in undesirable combustion products. Sulfur, for example, results in the production of sulpher oxide compounds.

8.6.1.2 Combustion Processes. Burning hydrocarbon fuels involves a chemical reaction of the hydrocarbons in the fuel with oxygen from the air. In an ideal chemical reaction, the combustion process releases heat, uses oxygen, and produces CO_2 and water.

In reality, there are complications which result in the production of additional, unwanted gases. When air is exposed to high temperatures, some of the nitrogen (N_2) and oxygen (O_2) molecules combine to make nitric oxide and nitrogen dioxide. This is independent of the particular fuel being burned. The hotter the flue gases and the longer the time at high temperature, the more NO, NO_2, and other oxides of nitrogen (NO_x) are formed. Also, if the flame is cooled prematurely, or if there is not enough oxygen available in the fuel-air mixture, elevated carbon monoxide (CO) levels can be emitted.

In general, combustion system designers attempt to control the flame temperature in a manner that the flame is hot enough for long enough so that all CO is converted to CO_2, while limiting the temperature to minimize the generation of NO_x.

Combustion of liquid and solid fuels has additional difficulties for the equipment designer. First, it is much more difficult to mix the air and fuel completely, so even if enough oxygen is available, there may be local areas of insufficient air supply, potentially resulting in elevated CO production or unburned hydrocarbons. Impurities in the fuel can also result in undesirable combustion byproducts. For example, nitrogen in the fuel will result in additional NO_x

production, inorganic material results in particulate matter, and sulfur results in sulfur dioxide and other sulfur compounds (SO_x). Internal combustion has much more complex combustion dynamics, greatly increasing the variety of combustion products and the difficulties in controlling emissions.

8.6.2 Internal Combustion Engines. Automobile exhaust contains a wide array of pollutants. Of primary concern is carbon monoxide (since vehicles can be a significant source of CO inside homes), but the exhaust also contains hydrocarbons, particulate matter, and NO_x. Automobiles left running in an attached garage, even with the overhead door left open, can be a major source of pollutants in the indoor space. A large fraction of the accidental CO deaths in homes is due to vehicles that are left running in attached garages. Even allowing a vehicle to warm up briefly inside the garage can cause large increases in the concentration of indoor CO and other combustion products. This is especially true because when a vehicle is started with a cold engine, the emissions can be many times higher than when the engine and emission control equipment is running at operating temperature.

As the vehicle's engine runs and continues to emit exhaust gases, the concentrations in the garage increase. If allowed, these exhaust gases enter the house. Air will move from the garage into the house due to wind or stack effect-driven pressures, or if the house is at a pressure lower than the air pressure in the attached garage. Often, the walls and doors between the garage and indoors are not sealed as well as exterior walls and doors, so a substantial amount of air entering the living space may be from the garage. Even if the garage walls are well sealed, air entry will still occur, although at a reduced rate. Another potential path for contaminant transport from garages to dwellings is leakage in HVAC systems and ducts located inside the garage.

In addition to vehicles left running in the garage, nearby roadways can also be a significant source of indoor pollutants. Heavily traveled roadways will have elevated concentrations of exhaust gases, with the concentrations decreasing with distance from the road. Studies have shown indoor CO concentrations increasing by up to 10 ppm during rush hour in houses on busy streets.[73, 74]

8.6.3 Vented Appliances. Combustion appliances fall into two broad categories, vented and unvented. They differ in that vented appliances are designed to have vent systems that carry the products of combustion outside the house, away from the occupants. There are several different types of vent systems, and it is important to follow the appliance manufacturer's installation instructions to be sure that an appliance has the correct type so that the combustion process operates correctly and the flue gases are safely carried outside. Failure to install the proper vent system can result in poor operation of the appliance, backdrafting, corrosion of the vent system, and/or hazardous conditions.

The various types of vent systems can be grouped into two broad categories: natural draft equipment and equipment with mechanically assisted venting, either induced or forced draft. Equipment with natural draft vent systems rely on the thermal buoyancy of the heated flue gases to carry them up the vent system and out of the house. Many atmospheric vent systems slope upward in the direction of travel of the flue gases, so the buoyancy pulls the combustion products in the desired direction. Appliances using natural draft venting rely on having enough air in the

space in which the appliance is located to provide proper combustion. Insufficient air, or excessive competition from other exhausting devices, can result in backdrafting of the combustion gases into the space. Gas-fired combustion appliances with natural draft include Category I natural draft and Category I fan-assisted units, as defined by the *National Fuel Gas Code*.[75]

Natural draft, direct-vent systems are also buoyancy driven, but they draw combustion air from the outdoors so that combustion air and venting are not dependent upon indoor air. Direct-vent systems generally are limited to installations where vent lengths and venting and combustion air supply are adequate to meet combustion requirements and as specified in installation instruction.

Equipment with mechanically assisted venting, use a fan to pull (induced draft) push (forced draft) the combustion gases out of the house, usually through a vent that runs horizontally. This equipment includes condensing appliances, where high-energy efficiency is achieved by extracting the maximum possible sensible and latent heat from the flue gases. However, some appliances with mechanically assisted venting, including mechanically vented water heaters, operate without condensing water vapor from combustion gases. Gas-fired combustion appliances with forced draft venting include Category III and Category IV units, as defined by the *National Fuel Gas Code*.[75]

8.6.4 Unvented Appliances. Unvented appliances deposit combustion byproducts directly in the space where the appliance is located, with no flue or vent to carry the combustion products to the outdoors. There are two major types of unvented appliances, space heaters and gas cooking appliances. Space heaters are designed to operate for an extended time and are allowed in most jurisdictions for installation in dwellings. Space heaters include appliances that are strictly for heating, as well as decorative hearth products that are designed to look like fireplaces.

Cooking ranges, which are most frequently used for shorter-term operation may also be used for extended periods of time as well, e.g., for roasting. Cooking appliances and their emissions will be discussed in Section 8.6.5; this section will address unvented space heaters.

Unvented space heaters produce heat, CO_2 and water, which are the only byproducts of ideal combustion. In addition, they produce CO and NO_x, various VOCs, and deplete oxygen. CO_2 is not a harmful contaminant at the concentrations that are expected to typically occur in residences. The water vapor emitted comprises a component of the overall moisture load, along with many other sources such as showering, cooking, houseplants, etc. At sufficiently high levels, humidity can cause IAQ problems; see Section 7. Moisture, for more discussion. CO and NO_2 emissions are regulated by ANSI Standard Z21.11.2[76], although the ANSI Z21.11.2 limit for NO_2 is based on preventing exposures three times greater than the recently-enacted EPA National Ambient Air Quality Standard (NAAQS) 1-hour outdoor standard. Research has shown that NO_2 is the pollutant from unvented space heaters most likely to exceed current standards, in this case the EPA NAAQS for outdoor air.[77]

The best way to avoid the risk of exposure to the combustion products emitted by “vent-free” (unvented) space heaters is to not install them in the first place. If they are installed, it is critical to use manufacturers’ recommendations regarding sizing[78] and usage. The sizing guidelines

specify recommended capacity (in Btuh/ft³ of space volume) depending on climate zone and dwelling tightness. Manufacturers also specify that these appliances are not to be used as the primary source of heating. Other agencies have released online documents cautioning residents about the use of unvented appliances. Examples include the Consumer Product Safety Commission,[79] U.S. Department of Housing and Urban Development[80], and Department of Energy/National Renewable Energy Laboratory.[81]

8.6.5 Cooking. Cooking food can release a wide variety of pollutants into the indoor air. Depending on the food and method of cooking, the type and amount of pollutants released can vary widely.

Many types of cooking result in the release of particulate matter into the air. Particle concentrations in the kitchen can easily exceed air quality standards during activities such as broiling fish, baking lasagna, frying tortillas, stir-frying, or cooking a fried chicken dinner. Using the self-cleaning feature of the oven can also produce high particulate concentrations.[74]

Cooking also produces large amounts of water vapor in many cases. Any type of boiling generates significant water vapor loads. Some cooking activities also produce acrolein, formaldehyde, $PM_{2.5}$, and polycyclic aromatic hydrocarbons (PAHs). These may occur due to the burning of food spills or residue on surfaces.[74]

In addition to the contaminants listed above, which occur for both electric and gas ranges, use of gas-fired stoves also increases concentrations of water and NO_x and CO.[82]

Overall occupant exposures to indoor contaminants from cooking have decreased in recent years. This has occurred for two reasons: less cooking by the average household and removal of gas pilot lights. The average number of meals cooked in the home has been decreasing. In 1993, 80.2% of all households cooked at least one hot meal per day.[83] By 2001, this number had decreased to 72.6%.[83] This was due to an increase in eating meals out of the home and an increased use of frozen and packaged foods.

8.6.6 Portable Combustion Equipment.[84] Portable combustion equipment includes portable generators and power tools using internal combustion engines. These types of equipment represent a large and increasing source of CO poisoning in the United States. Since they are portable (i.e., not installed within the building envelope and, as a result, not readily controlled through codes) it is not practical to design a ventilation system to address the contaminants emitted by these devices. There are numerous examples of poisonings and fatalities associated with such equipment in disaster recovery situations or power outages where the equipment is operated indoors or in close to a dwelling.

9. INDOOR AIR QUALITY CONTROL

9.1 Background. Ventilation is just one available strategy for IAQ control and is often not the best one. Source control (i.e., eliminating or minimizing sources of indoor contaminants) is often considered an essential IAQ control strategy. Ventilation may be applied either through general (dilution) ventilation or local exhaust ventilation. Some contaminants can be removed through

filtration. Contaminant monitoring can contribute to ensuring IAQ either through direct feedback control or through alarms that can warn of a potentially unhealthy situation.

EPA developed a voluntary new home IAQ labeling program, EPA Indoor airPLUS[85], which requires verified compliance with a comprehensive set of new home construction specifications. The Indoor airPLUS Construction Specifications are intended to "contribute to improved IAQ in new homes compared to standard code-built homes." The latest revisions to the Indoor airPLUS Construction Specifications are posted on the Indoor airPLUS website.

For existing homes, EPA published specifications in Healthy Indoor Environment Protocols for Home Energy Upgrades[86] ". . . to provide practical guidance on improving or maintaining indoor air quality and indoor environments during home energy upgrades, retrofits or remodeling."

9.2 Source Control. Source control can take a variety of forms, depending on the nature of the source.

9.2.1 Vented Combustion Appliances. Preventing entry of combustion products from vented appliances into the home is typically achieved by providing venting of these products directly to the outdoors by means of a flue. The flue should be designed with a minimum of bends and with a minimum length. Providing sufficient make-up air avoids depressurization conditions inside the dwelling and also reduces the potential for backdrafting of these appliances.

Sealed combustion (direct-vent) appliances and induced and forced draft appliances also reduce the risk of combustion products entering the home.

9.2.2 Moisture Control. The best way to control colonization of all biological contaminants is to control moisture sources from outside and within the building. Effective moisture control addresses both bulk water entry into the building and control of indoor relative humidity and interior surface temperatures to prevent condensation. Detailed, practical guidance for controlling all forms of moisture in buildings is provided in the EPA's *Moisture Control Guidance for Building Design, Construction and Maintenance*.[113]

9.2.2.1 Elevated Indoor Relative Humidity. Bathrooms and kitchens, by their nature, are locations that periodically are subject to high moisture loads. Local exhaust ventilation in these locations can be used during the moisture-producing periods to remove this excess moisture from the home. To achieve this, all local exhaust devices should be vented to the outdoors with a minimum of duct bends and length. Recirculating range hood fans do not remove any moisture and should not be considered part of a strategy for reducing elevated indoor relative humidity.

9.2.2.2 Water. Concentrations of water on a surface or in building materials can cause damage to buildings and can evaporate and increase the indoor relative humidity. Leaks should be repaired as quickly as possible; spills should be cleaned up promptly; and porous materials that become wet should be allowed to dry as quickly as possible, including temporary placement outside if practical.

9.2.3 Radon Control. Radon enters the home with soil gas. Therefore, to prevent radon entry, soil gas should not be allowed into the home. Soil gas entry can be prevented by exhausting the

soil gas directly to the outside, by pressurizing the space directly above the ground, or by sealing off the air pathways between the foundation space and the living space. If exhaust is used, the best method is to use a fan designed for soil gas removal below the slab floor (sub-slab depressurization) or beneath a ground cover (for homes with dirt floors) with a duct that discharges above the roof of the home. Effectiveness of radon control has been evaluated elsewhere.[118]

9.3 Filtration

9.3.1 Background. Contaminants that can be removed by filtration in residential environments take the form of either particles or gases. Particles larger than 10 microns, or micrometers (µm), in size are generally considered to be visible to the naked eye. These larger particles are relatively heavy, large-mass particles that do not remain airborne, but drop out on horizontal surfaces. Particles smaller than 10 microns generally remain airborne due to the forces of Brownian movement, diffusion, and electrical charges. Thus, they do not deposit unless intercepted by filtration or their inherent charge is altered, causing them to deposit on surfaces. For additional background, see Chapter 29, Air Cleaners for Particulate Contaminants in *2012 ASHRAE Handbook—HVAC Systems and Applications*.[87]

Particles less than 2.5 microns (µm) ($PM_{2.5}$) are considered to be respirable, as they will elude the filtering mechanisms of the upper respiratory system and will be inhaled into the deep lungs (e.g., asbestos). $PM_{2.5}$ can be removed using MERV 10 and higher filters.

Particles smaller than 0.1 microns (µm) are called ultrafine particles (UFP) and are primarily generated by combustion processes from outdoor (automobile and diesel exhaust) or indoor (cooking, gas appliances, fireplaces or candles) sources. UFPs have also been shown to increase mortality from cardiovascular and respiratory disease.[32] UFPs can be removed using MERV 13 and higher filters, and by mechanically exhausting indoor UFPs from electric and gas cooking appliances and other gas appliances.

Elements in the airstream that are in the gaseous phase are less than .001 microns (µm) or in the angstrom (Å) range are “molecules in solution” and behave as part of the airstream. They are not altered or withdrawn from the airstream unless captured by weak electron polarization forces called “van der Waals” sorption forces. They may also be destroyed or altered by chemical reaction with other airborne molecules.

Because residential filtration is almost exclusively focused on the removal of particles, this discussion of filtration details common particle removal technologies. (See Chapter 46, “Control of Gaseous Indoor Air Contaminants,” in the *2011 ASHRAE Handbook—HVAC Applications*[87] for more information on gas-phase air cleaning.)

9.3.2 Particles. Table 9-1 lists particles that are common in the residential environment, including their source and their size.

9.3.3 Particle Filtration Technologies. The following discussion outlines the various control technologies for the removal of particles from the airstream. Table 9-2 describes the control

mechanisms and the applicable target of control. Table 9-3 iterates the advantages and disadvantages of each approach.

Mechanical (or arrestance) filters may be used in central filtration systems as well as in portable units using a fan to force air through the filter. Arrestance filters capture particles by several physical mechanisms. Larger particles such as lint and fibers impact or “impinge” upon the filtration medium by colliding with the fibrous mesh. Smaller particles are “strained” out of the airstream by increasingly smaller openings in the filter pack. The higher efficiencies are attained by creating a denser matte of fibers and/or using increasingly finer fibers. Finally, very small submicron-sized particles are captured by “diffusion” toward the surfaces of the filtration medium (generally independent of airflow) where they are captured by natural electron interaction between surface charges of superfine particles and the filtration fiber media.
This latter mechanism is the predominant factor in the effectiveness of the highest efficiency mechanical filters. In general, particle removal as a function of particle size is U-shaped, with better removal of larger particles due to impingement and very small particles due to diffusion, with intermediate-sized particles more difficult to capture.

TABLE 9-1 Common Particles of Concern in Indoor Environments

CONTAMINANT	SOURCE AND DESCRIPTION	SIZE (μ)
Pollen	Products of plant kingdom bloom and reproduction. Typical: oak, pine, grass, corn, ragweed, goldenrod	10-100 μ
Household dust	Made up of lint, fibers, and shed skin. From space components, linens, clothing, human/animal occupancy and their activities.	Visible >10 μ
Allergens	Products of life chemistry. Household allergens are from cats, dogs, birds, or other household pets	<10 μ
Mold spores (viable particle)	Viable particles from reproductive process of fungi. From earth, foliage, decay matter, water. Potent element is mycotoxin. Many species-- though only a few dozen amplify indoors.	1-20 μ (mean size 3μ)
Bacteria (viable particle)	Single cell plant microbials. Human pathogens from human contact, water sources/airborne aerosol. Potent ingredient—Endotoxin. Typical: Legionnella sp., Tuberculosis bacillus.	1 μ critical dimension
Viruses	A nucleic acid molecule in a protein coat. Human pathogens from human or animal contact—may be carried on vector particles of 1μ or greater in size or, as a “droplet nuclei” which is the virus and the evaporated solids from the solution it was expelled from the human within (usually mucus).	<1 μ
Mite/insect particles	Microscopic insect parts or airborne fragments of feces. Typical—dust mites, cockroaches.	5-20 μ

ETS	Particulate (visible) component of tobacco smoke. Source—cigar and cigarette smoking—second hand smoke.	.1-3 μ
RSP	Respirable Suspended Particles—Condensation nuclei, from chemical reactions or chemical phase change. From internal combustion engines, combustion appliances, fires, volcano, wave action. Commercial products—print toner.	<2.5 μ
Asbestos	Natural geological fiber—naturally occurring in outdoor air. Used indoors till 70s in buildings for fire retardation. Regulated.	1-3 μ
UFP	Ultrafine particles – from cooking (electric and gas) and indoor and outdoor combustion sources.	<0.1 μ

TABLE 9-2 Particle Filtration Technologies

CONTROL TECHNOLOGY	CONTROL CLAIMED	TECHNOLOGY DESCRIPTION
Low efficiency arrestance panel filters	Larger particles, low efficiency	Pads, rolls, blankets, and panels using a relatively coarse filter matte of larger fiberglass, synthetic materials, natural fibers, or metal. Widely used as general ventilation filters and as prefilters for higher efficiency types. Not reported using 52.2-2012[60] (i.e., less than MERV 4).
Medium efficiency pleated panel filters	Larger particles, better efficiency	Uses denser filter fabric or media and some form of extended surface area through pleating or shaping (e.g. into cubes or pockets. Usage as above. MERV 5-8.
Enhanced electret arrestance filters	Improved efficiency with small particles	Filter media treated with factory induced or electro/mechanical electrostatic properties. Enhances lower efficiency filters to better control small particles that respond to sustained electrical charge deposition. Some fungal control. MERV 8-16.
High-efficiency bags, deep pleats, cartridges, mini-pleats	Smaller particles, good efficiency, Microbial control	High efficiency filters using filter media of microfine fiberglass, synthetic, or paper in deep pleating configuration. Applied in healthcare, manufacturing, commercial buildings, and as prefilters for HEPA/ULPA. Used in cartridge form in clean air devices. MERV 9-16.
Minipleat, separator and separatorless HEPA/ULPA	Ultra fine particles, excellent efficiency, microbial control	Highest efficiency arrestance filters having excellent control of sub-micron particles. Applied in healthcare, clean-rooms, specialty manufacturing, CADs. ULPA is same as HEPA but more stringent quality control and testing rigor. MERV 17-20.
Electrostatic Precipitation	Good efficiency with small	The air stream and airborne particles are exposed to a high voltage corona. Small particles are charged and plated (ground) out on deposition plates. First used in healthcare—now obsolete in this

	particles, microbial control	application. Used in residential and clean air devices. No MERV level. Produces ozone.

TABLE 9-3 Comparison of Particle Filtration Technologies

TECHNOLOGY	PRO	CON
Low efficiency arrestance panel filters	Lowest cost Lowest static pressure loss Fully disposable	Lowest efficiency Low dirt holding capacity Short life—frequent change Not reported by MERV
Medium efficiency pleated panel filters	Lower cost Lower static pressure loss Reported by MERV Fully disposable Adequate prefilter	
Enhanced electret arrestance filters	Somewhat higher cost Low static pressure loss Some are cleanable Enhanced efficiency over above base media. MERV rated Adequate as prefilters	Insufficient efficiency for Clean Air Device Loses charge with air exposure Cleaning not fully effective
High efficiency bags, deep pleats, cartridges, mini-pleats	Higher efficiency Acceptable efficiency for Clean Air Device Less costly than HEPA Lower resistance than HEPA Higher dirt capacity than lower baseline MERV rated	More costly than lower efficiency filters Requires more airstream depth Higher air resistance than lower efficiency
Minipleat, separator and separatorless HEPA/ULPA	High efficiency—excellent small particle control DOP rated	More expensive than lower efficiency Highest air resistance of all arrestance type filters

	High capacity Long life with minipleat version	Expensive replacement Prefiltration recommended
Electrostatic precipitation	High efficiency @ small particles Low air resistance/static pressure loss Lower blower noise Cleanable by owner No replacement cartridge cost	High first cost Prefiltration required Cleaning is frequent and labor intensive Low efficiency on large particles Shorts out/sparks on large particles Produces ozone

Arrestance filters are of the following major types:

9.3.3.1 Low-Efficiency Arrestance Panel Filters. Panel filters usually contain a large fibrous medium that can be dry or coated with a viscous substance such as oil to increase particle adhesion. Dry-type filter media may also consist of open-cell foams, nonwoven textile fabric, paper-like mats of glass or cellulose fibers, animal hair, or lofted synthetic fibers. They may also consist of slit and expanded aluminum screening. Media filters of various materials are available in a wide range of sizes and thickness. The typical, low-efficiency furnace filter in many residential HVAC systems is a flat filter, one-half inch to one-inch thick, which adequately collects large visible particles, such as lint, but removes a negligible percentage of the smaller and problematic respirable-size particles. It was originally used to restrict flammable matter like animal hair from causing fires when exposed to the firebox of hot air furnaces. Hanley showed the low efficiency of the typical furnace filter compared to other types of air cleaners over the 0.01–10 micron diameter size-range.[88] The efficiency of all of the units varied with particle size, but the typical furnace filter had especially low efficiency against all particle sizes.

A subcategory of this class is marketed as an “electrostatic” filter (not to be confused with the “electronic air cleaner” or “electret” media discussed later in the section). This category of panel filter is marketed as an enhanced efficiency filter due to electrostatic properties of the synthetic fiber media. The course fiber media is charged either in the fabrication process, or by low-voltage electrical current as installed to enhance its capture of smaller particles through electrostatic attraction. The media is claimed to be “washable” in soap and water, which supports the “permanent filter” claim. The disadvantage of the filter is that it face-loads easily like other panel filters, resulting in frequent service cycles. Further, the washing process relieves the surface charge of the media negating any enhancement.

9.3.3.2 Medium-Efficiency Pleated Panel Filters. One of the most effective ways to increase the particle collection efficiency of mechanical filters is to increase the filter media thickness or density using small fibers. This creates smaller media penetrations and increases the screening or straining effectiveness. However, any increase in filter matte density significantly increases resistance to airflow, causing decreased airflow through the filter. The most effective approach to

overcoming this problem is to extend the surface area by pleating the filter medium. This lowers the airflow velocity through the filter and decreases overall resistance to airflow, such that static pressure drop (energy loss) is reduced dramatically. Additionally, pleating of filter media increases the total area available for dirt holding and, thus, extends the capacity and useful life of the filter. As a result, the efficiency of pleated media filters is much higher than for other dry-type panel filters. This class of filter is generally applied in a 2 in. or 4 in. depth in commercial applications, although there are now a number of suppliers of 1 in. pleated filters for residential application. A deeper 5-6 in. pleat is used in several whole-house filter units marketed with an integral plastic or sheet metal retainer housing to facilitate installation into return air ductwork. Hanley[88] demonstrated the efficiency of a pleated paper filter over the 0.3–10 micron diameter size-range compared to a typical flat furnace filter. The medium-efficiency pleated paper filter exhibited dramatically improved efficiencies in the larger particle sizes, but still dropped off in the submicron range.

9.3.3.3 Enhanced Electret Arrestance Filters. Enhanced electret arrestance filters use synthetic fibrous media with permanently charged fiber surfaces. This media, called “electret,” can be fabricated into flat-panel filters, pleated-panel filters, extended-media pocket filters, or even deep-pleated cartridge filters, like HEPAs. The synthetic media is inherently charged in the manufacturing process and retains the charge that attracts fine airborne particles that are then trapped and retained within the fibrous matte in the more conventional methods of impingement and diffusion employed by other dry-type filters. The advantages of an “electret” media filter are the filter’s relatively low pressure drop with higher efficiencies, when compared to other conventional vitreous fiber substrates. This is because the charged electret media provides higher initial efficiency using somewhat larger fiber size than the competitive media. The disadvantage and flaw of the electret-type media is the drop in efficiency (sometimes dramatic, depending upon the application conditions) during the loading life cycle once installed in an ambient airstream. Apparently, specific components of ambient air, such as selected VOCs or super-fine nanoparticles, can neutralize the fiber charge reverting the media to the lower-efficiency levels of nonelectret media. Hanley[88] showed the decreased efficiency of an electret filter with increased use and dust loading. To recognize this drop-off effect, ASHRAE Standard 52.2[60] incorporated an initial “conditioning” step into the loading protocol for the determination of the minimum performance point. Subsequent experience has indicated that the original conditioning protocol may insufficiently reflect the actual performance drop.

9.3.3.4 High-Efficiency Extended Media Filters. High-efficiency extended media filters take the surface area extension process beyond the pleated filter into deeper configurations.
This is done through deep pleating in 6 in. and 12 in. depths or the fabrication of the media into individual pockets that are then supported with rigid plastic or metal frames. Because of the media surface area, much higher efficiencies are attainable with acceptable pressure drops. Normally, extended media cartridge filters are 12 in. depth and pocket filters can be up to 30–36 in. in depth in the direction of airflow. One subclass of this filter range is referred to as the “minipleat,” which employs a filter paper media that is tightly pleated in a 1 in. panel that, in turn, is v-banked into a 12 in. deep cartridge and retained in a rigid plastic frame. Because of its very high surface area, this version of filter exhibits lower pressure drop than other filters of similar efficiency. Because of their size and pressure drop requirements, this entire class of filters is not normally installed in residential HVAC systems. However, special-sized units in this

efficiency range can be used in self-contained portable air cleaners. Usually, they are configured or engineered into the specific size and/or shape that best fits the air cleaning device.

9.3.3.5 HEPA Filters. HEPA air filters, formerly called high-efficiency particulate arrestors, are the ultimate of extended-surface media filters. HEPA filters were originally developed during World War II to prevent discharge of radioactive particles from nuclear reactor facility exhaust. They have since become a vital technology in industrial, medical, military security facilities, and clean rooms. They have grown in popularity for use in portable residential air cleaners that can compensate for the high pressure drops imposed by these filters.

A HEPA filter has been traditionally defined as having a minimum particle removal efficiency of 99.97% for all particles of 0.3 micron diameter, with higher efficiency for both larger and smaller particles. This rating is determined using a test method promulgated by the Institute of Environmental Sciences and Technologies (IEST) and is comparable to the MERV 17 class or greater. The filtering media of a HEPA filter is made of submicronic glass fibers in a thickness and texture very similar to blotter paper. More recently, filters made in the same physical style using less-efficient filter paper based on synthetic fibers, including electret media, are mislabeled as HEPA filters or described as “HEPA-type” filters. Their actual efficiency may be 55% or less at 0.3 microns, falling into the MERV 13–14 range. While still very good filters when compared to conventional panel types and even extended-media pocket filters, these lower-quality filters have higher airflow, lower efficiency, and lower cost than the original version.

The true HEPA filter causes a very high pressure drop, and all versions require prefiltration in order to extend their life. Also, HEPA filters are generally not applied to residential HVAC systems due to their size and horsepower requirements, other than in by-pass units that provide for supplemental booster blowers. However, they can be incorporated into air cleaning devices since the blower is integral to the device. The disadvantage of HEPA filters is their need for a powerful fan that leads to increased energy costs compared to less efficient filtration systems. Retail prices for replacement HEPA filters for residential by-pass units range from $100–400, depending on size, with replacement typically needed once every 3-5 years, depending on pre-filters used. The major advantages of the original HEPA filters, however, include high efficiency, which actually increases with use, and a long maintenance-free life cycle of up to five years when used with a prefilter selected from one of the versions described above. Consumers should be cautious about claimed “HEPA-like” performance to ensure that the term is being property applied. Likewise, be wary of terms like “HEPA-style,” “HEPA-like,” and “HEPA-type” as they are used to imply higher performance than they deliver.

9.3.3.6 Electronic Air Cleaners. Electronic filters, generally marketed as electronic air cleaners (EAC) and formerly referred to as electrostatic precipitators, employ an electrical field to trap particles. Like mechanical filters, they may be installed in central filtration systems as well as in portable units with integral fans.

Electronic air cleaners produce ozone which is a contaminant that can contribute to chronic respiratory health issues and increased mortality.[29,31] Addition of a carbon filter to an electronic air cleaner is recommended to reduce ozone emissions.

Electrostatic precipitators are the most common type of EAC. They employ a one-stage or a two-stage design for particle collection. In the less expensive but less effective single-stage design, a charged medium acts to both charge and collect airborne particles. A two-stage design employs a high-voltage electrode or wire, which creates a charge field and places an electron charge on the incoming airborne particles. In the second stage, the charged airborne particles are drawn between a series of oppositely charged metal plates, which attract the charged particles from the air causing them to precipitate onto the metal plates. Collection efficiency is a function of the area of the collecting plates, the flow rate, and the strength of the electrical field.[89] The airflow remains constant with use, but the particle capture efficiency declines rapidly as the charged collector plates become coated with particles. Cleaning the plates thoroughly restores the plates to near initial efficiency but cleaning should be done regularly and frequently, i.e., weekly and not monthly, as indicated by many of the manufacturers. Work by Hanley at the Research Triangle Institute also shows that over time the EAC slowly loses its ability to charge particles and return to clean efficiency because of the build-up of silicone deposits on the electrical ionizing grid wires.[90]

A simpler form of EAC is the negative ion generator. Several versions of negative ion generator-type air cleaners are available. The simplest types use static charges to remove particles from indoor air. They operate by charging the particles in a room, which become attracted to and deposit on walls, floors, tabletops, curtains, occupants, etc., where they may cause soiling problems.

More advanced units are theoretically designed to reduce soiling in a room. They generate negative ions within a space through which air flows, causing particles entrained in the air to become charged. The charged particles are then drawn back into the cleaner by a fan, where they are collected on an electrostatically charged panel filter. In other ionizers, a stream of negative ions is generated in pulses, and negatively charged particles are drawn passively back to the ionizer, which contains a positively charged sleeve or cover.

ANSI/AHRI 680-2009, Performance Rating of Residential Air Filter Equipment[91], is a recent consensus industry standard has been developed as an alternate rating system to ASHRAE 52.2. It includes a procedure to measure electronic air cleaner filtration efficiency.

9.3.4 Discussion of ASHRAE 52.2-2012.[60] ASHRAE Standard 52.2 was developed in response to the weaknesses of the Atmospheric Dust Spot Test. The newer test method provides improved performance data and selection criteria that enable classification according to minimal size fraction efficiencies. The test method provides for combining the efficiencies within size clusters to allow a combined single classification called MERV (Minimum Efficiency Rating Value). ANSI/AHRI 680-2009[90] is a recent consensus industry standard has been developed as an alternate rating system to ASHRAE 52.2-2012.

9.4 Contaminant Monitoring

9.4.1 Background. There are a number of contaminant monitoring methods for research purposes, but in general, there are very few practical sensors applications available for

monitoring common residential contaminants for IAQ control purposes. The only common contaminant sensor applications are humidistats, CO_2 controls, smoke alarms, and CO alarms.

9.4.2 Humidistats. Humidistats are available for three uses. The first is to automatically operate local exhaust fans, such as kitchen and bathroom exhaust, when humidity levels are above a set point. A second use is to operate humidifiers if humidity is below a set point in winter. A third is to operate air conditioning at a low-flow rate and for extended runtimes when the humidity is above the set point.

9.4.3 CO Alarms. CO alarms are, like smoke alarms, life safety devices intended to warn of potential life-threatening situations. Most models do not trigger at levels as low as those identified in Section 4. CO alarms are required in residential buildings in many states and installation is recommended by many federal agencies and national organizations including:

- U.S. Consumer Product Safety Commission
- U.S. Center for Disease Control
- U.S. Fire Safety Administration

CO alarms with battery backup should be installed in any residential building regardless of the presence of combustion appliances as required by ASHRAE 62.2-2013[1]. ASHRAE 62.2-2013, Section 6.9, states: "A carbon monoxide alarm shall be installed in each dwelling unit in accordance with NFPA 720, *Standard for the Installation of Carbon Monoxide (CO) Detection and Warning Equipment*, and shall be consistent with requirements of applicable laws, codes, and standards."[1]

10. MECHANICAL VENTILATION SYSTEM DESIGN

10.1 Introduction. Occupant comfort, energy efficiency, ease of use, service life, first- and life-cycle cost, value-added features, and indoor environmental quality should be considered when selecting a strategy and system. Ventilation systems and strategies that result in discomfort (e.g., due to noise or drafts) or excessive energy usage may not be utilized by occupants as intended, possibly resulting in poor indoor air quality.

This section addresses the HVAC (and related) systems as one potential cause of reduced quality of indoor air and as a control mechanism. Careful design, operation, and maintenance are necessary to provide optimal effectiveness.

10.2 Design, Installation, and Build Out. This section focuses on design issues related to the HVAC system. System design cannot be separated from envelope design or consideration of other sources.

10.2.1 Pressure in the Living Space. All exhaust, supply, or air-handling fans have the potential to change the pressure of the living space relative to outdoors. High-volume fans such as the air handler and some cooking exhaust fans can cause high levels of depressurization particularly in homes of tight construction. Consideration of these effects is essential in the design process.

Depressurization of the living space relative to outside may cause back-drafting of combustion appliances and the migration of contaminants (such as radon or other soil gasses, car exhaust, insulation particles, etc.) into the living space. In hot, humid climates depressurization can result in moisture intrusion into building cavities, potentially causing structural damage and fungal growth. Conversely, pressurization of the living space can cause condensation in building cavities in cold climates, resulting in damage to the structural integrity of the home.

Excessive pressures may best be prevented by balanced ventilation systems combined with tight ducting systems accompanied by adequate return pathways for all supply air on air-handling devices. When pressure-relief openings are used (such as thru-wall or thru-window devices), their effect on comfort and energy consumption should be considered. It should also be considered that occupants may block off pressure-relief openings.

Section 6.4 of ASHRAE 62.2 uses a simplified, prescriptive set of conditions to determine if compensating outdoor air (referred to as “makeup air” or “MUA” by the model codes) is required to provide acceptable indoor air quality. Based on ASHRAE 62.2, MUA is required when the following conditions exist:

1. Natural draft or solid-fuel burning appliances are located within the pressure boundary, and
2. The two largest exhaust appliance capacities exceed 15 cfm/100 ft^2 (excluding whole house cooling fans meant to operate only when windows or other air inlets are open; this capacity is equivalent to 300 cfm in a 2000 ft^2 dwelling)

These conditions are easily achieved in a typical dwelling unit, with domestic clothes dryers exhausting 100-200 cfm and kitchen range hoods exhausting more than 100 cfm.

While the standard is clear on when MUA is required, it is silent as to the design and performance specifications of these systems. Assuming that the primary objective of providing MUA is to limit excessive depressurization of combustion appliances, a thoughtful design should provide MUA at sufficient rates so as to not exceed industry recommended depressurization limits for combustion appliances. The following depressurization limits are recommended by the Building Performance Institute’s Building Analyst Professional Standard based on the type of space or water heating combustion appliance located within the pressure boundary of the dwelling:

- Separately-vented natural draft water heater: -2 Pa
- Common-vented natural draft water heater: -3 Pa
- Individually vented, natural draft; or common-vented, natural draft and mechanical draft: -5 Pa
- Individually vented, mechanical draft: -15 Pa
- Direct vent/sealed combustion: -50 Pa

Safety of combustion appliance venting should always be verified by a rigorous spillage test, sometimes referred to as a stress test.

From the results of a blower door test, the designer can determine the quantity of MUA that is expected to be provided naturally through infiltration across the building envelope at the design depressurization limit. The deficiency between the design exhaust rate and the infiltration

provided at the design depressurization limit should be provided through a dedicated MUA system. Reducing the design depressurization limit has the effect of increasing the quantity of MUA that should be provided through the dedicated MUA system.

Options for dedicated MUA include passive (an opening equipped with a damper) and active (an opening equipped with a damper and fan-assist). Care should be given to the type of damper selected. Gravity and barometric dampers are not recommended because they are not likely to engage at pressure differentials of less than 5 Pa. Motorized dampers are recommended because they are not affected by pressure differentials, may be required by the model code, can be automatically closed to conserve heating and cooling energy when exhaust appliances are not in use, and will not cause sensory irritation to occupants from flapping in wind events. Other options for the designer include pre-conditioning and dehumidification of the outdoor air, though these can increase the cost of operation and are not likely required by minimum building codes and standards.

Sizing of openings should incorporate considerations for system losses (affected by duct dimensions, type, and length; dampers; terminations, etc.), and can be calculated based on the Darcy Weisbach equations found in the *2013 ASHRAE Handbook—Fundamentals*[96] or with design calculators available from damper manufacturers. MUA should be provided to a space that freely communicates with the exhaust appliance, whether directly in the vicinity, through ducts or grilles, or in another space that communicates through adequately sized openings. Systems that are integrated with the duct work of forced air furnaces should observe any manufacturer restrictions related to minimum return air temperatures.

10.3 HVAC System Design, Installation, Maintenance, and Operation. It is important that HVAC systems be designed, built, operated, and maintained in a way that discourages the growth of biological contaminants. This means that condensate drain pans need to be sloped to the drain, condensate drains be maintained free of obstructions, cooling coils be free of dirt and other obstructions, and that any cause of moisture inside ducts be investigated and eliminated. It is particularly useful for any inside cooling coils to be installed in a manner that makes cleaning practical.

It is also important that HVAC systems be designed, built, operated and maintained in a way that reduces or eliminates the migration of contaminants into occupiable spaces. This means that within the pressure boundaries of the dwelling, pressurization of spaces containing contaminants and the depressurization of adjacent spaces should to be avoided. Return systems that use building cavities often draw air from multiple unknown sources. Keeping duct systems out of spaces with known sources, such as garages, is an effective strategy to avoid introducing contaminants and moisture into living spaces.

When contaminants are present in the home, air-moving equipment associated with heating or cooling rapidly disperses the contaminants through the home. This effect both lowers peak concentrations and distributes the contaminants to other spaces. This effect should be taken into account when considering source control.

10.3.1 Mechanical Ventilation System Design, Installation, Maintenance, and Operation. The concentration of indoor contaminants can increase if ventilation systems are inadequately designed, installed, maintained, or operated, or if strong local contaminant sources are not isolated, locally ventilated, or controlled. Manual switches associated with a continuous ventilation system should have a clear label such as, "This controls the ventilation system of the home. Leave on except for severe outdoor contamination." Section 13 contains guidelines on Operations and Maintenance procedures and documentation.

10.3.2 Effect of Outdoor Conditions on Moisture Removal. During periods when the outdoor air has a higher absolute humidity than the air to be exhausted, neither natural nor mechanical ventilation provide good moisture control. The best and most cost-effective moisture control may be a mechanical cooling or dehumidification system. High outdoor air moisture content suggests the shutting down of mechanical exhaust; however, typical mechanical cooling systems do not provide for removal of contaminants other than moisture and filtration of particles. When elevated indoor humidity conditions occur only occasionally, special provisions may not be necessary.

10.3.3 Considerations in Hot, Humid Climates. Providing controlled ventilation in hot, humid climates can lead to or exacerbate moisture-related problems in air-conditioned homes if adequate dehumidification is not provided by the air-conditioning system or other process, such as a supplemental dehumidifier. Failure to control humidity levels in hot, humid climates can lead to occupant dissatisfaction and poor IAQ—as well as decreased durability and maintainability in severe cases—by allowing the growth of microbiologicals. ASHRAE Standard 160 provides guidance for preventing mold growth.

Outdoor air will add to the moisture load of the dwelling, but is nevertheless required for adequate IAQ. Reducing outdoor airflow below the minimum requirements of Standard 62.2[1] is not an acceptable moisture-control strategy. Correct sizing of the air-conditioning systems, reducing airflow across coils, effective coil capacity matching, and the use of a dehumidifier are all acceptable strategies to remove moisture generated by occupants as well as moisture brought into the dwelling by ventilation.

It has proven difficult to control indoor humidity within comfort limits in enclosures with leaky ductwork or leaky air handlers, especially when located outside the conditioned space. This additional outdoor air exacerbates moisture-control problems. Many dwellings in hot, humid climates currently have excess quantities of outside air inadvertently brought into building enclosures. Leaky ductwork and equipment located in vented attics, vented crawl spaces, and garages can lead to air-change rates several times greater than desired. It is recommended that ductwork and equipment be placed inside the conditioned space (pressure boundaries) or be well sealed and properly insulated and tested to reduce the induced infiltration and unwanted heat transfer. These steps should be taken in conjunction with providing outside air in a controlled manner in sufficient quantities to meet this standard. Provisions for moisture control and ventilation should be considered together in the design of the dwelling.

Residences with high-performance glazing systems and thermally efficient roof and wall assemblies can have sensible loads so low that traditional air-conditioning systems have trouble

providing humidity control. Under partial load conditions, the required outdoor air and occupant activities will often produce a larger latent load than can be handled by the air-conditioning systems. Under such circumstances, independent dehumidification control should be used.

10.3.4 Kitchen Range Hoods. Studies have demonstrated that gas cooking appliances emit pollutants to a living space, including carbon monoxide, NO_x, NO_2, $PM_{2.5}$ and UFP. Concentrations of these pollutants rise with an increased amount of cooking.[106] Kitchen ventilation, especially range hoods, can help to remove these contaminants. However, it has been shown that kitchen range hood ventilators often do not clear the indoor air as well as expected. Capture efficiency (the fraction of generated pollutants moving through the range hood) can range from less than 15 percent to over 98 percent, depending on airflow rate, hood design, and burner position, and the user's choice of the burner to use.[107]

Current standards for range hood performance do not consider capture efficiency as a metric and therefore do not fully address performance efficiency. Studies show that regular use of range hoods can reduce occupant exposure to cooking and burner-generated contaminants, especially if the back burners are used.[107] Capture efficiency is enhanced by increasing airflow through the hood and extending the hood over the range-top burners, including those at the front of the range. At high airflow rates, make-up air as discussed in section 10.2.1, may be required to avoid depressurization of the space.

10.4 Selecting the Whole-Building Ventilation System. With whole-building mechanical ventilation systems, it is important to consider where the outdoor air comes from, how it enters the dwelling, how it is distributed, and how it leaves the dwelling. Systems that are uncomfortable, expensive to operate, unsafe, noisy, or in other ways unacceptable to the occupants are not likely to be used.

There is no air distribution requirement in Standard 62.2.[1] However, the distribution of exhaust and outdoor air supply is an important consideration. Air distribution can be supplied either by a distribution system provided for that purpose, a ducted thermal distribution system, or connections between spaces when the spaces are sufficiently linked to the air inlets and outlets.

Whole-building ventilation may be provided by single or multiple fans operating continuously or intermittently. These fans may also be the fans providing the local exhaust ventilation. Advanced timing and fan-speed controls can provide continuous or intermittent low-speed whole-building ventilation and allow for operation at higher speed local ventilation when needed.

10.4.2 Energy Consumption. Although energy consumption is not within the scope of Standard 62.2, energy consumption of the mechanical ventilation system and the factors that influence that consumption should be considered. These factors include:

- duct flow resistance (this is captured in the total pressure, p_t)
- fan flow, Q_f which is dependent on the fractional on time
- fractional on time, f
- combined fan/motor/cabinet efficiency, e_{fm}

These factors are related to the energy consumption through the following relationships (IP) (Note that the energy consumption to temper outside air is not included in these equations):

$$FHP = Q_f\, p_t / (6370\, e_{fm}) \qquad (10\text{-}1)$$

where

FHP = fan horsepower
Q_f = fan flow (cfm)
p_t = total pressure (in of water)
ef_m = combined fan/motor/cabinet efficiency

$$E_f = FHP\ 8760\ NDS\ 0.7457 \qquad (10\text{-}2)$$

where

E_f = fan energy consumption (kWh)
8760 = annual hours
NDS = net duty cycle (fractional on time for single-duty fans)
0.7457 = kilowatts per horsepower

The electrical energy required to operate the system and the energy required to temper the outside air introduced through ventilation should be calculated as part of system design and selection.

10.4.3 Supply Ventilation. In a supply ventilation system, there is usually a single air intake for the ventilation air, which is then dispersed through the dwelling either by a dedicated duct system or by using the thermal distribution system. A supply ventilation system allows the filtration of outdoor air, which can remove pollen, dust, and other contaminants.

Exhaust pathways are normally provided by envelope leakage, exhaust stacks, and flues. Supply ventilation can result in indoor pressurization, which may be unacceptable in cold climates. Supply ventilation can partially mitigate radon entry or back-drafting problems and may reduce interstitial moisture problems in hot, humid climates.

In temperate or cold climates, the supply air, if delivered directly to rooms without tempering, can cause thermal discomfort or drafts. Energy recovery from the exiting air is not possible. When a dedicated duct system is used, the cost of a supply ventilation system is increased.

Primary advantages of supply ventilation are the known ventilation air distribution air pathways, the known source of outdoor air, and the option of outdoor air filtration. A significant drawback is the common use of a high-energy use fan (often the conditioning system air-handler fan). However, if the central system air handler is used, other advantages of particle removal by recirculation filtration, and homogenization of comfort and air quality conditions, can be corollary benefits. In any event, it is recommended that an efficient, variable speed type fan be utilized so as to reduce energy use during ventilation-only operation.

Additionally, if the system does make use of the air-handler fan, special controls are required to ensure that ventilation is provided when thermal space conditioning is not needed. The conditioning system might already run enough under more severe heating and/or cooling conditions, but additional runtime will be needed most under more mild conditions.

10.4.4 Exhaust Ventilation. In an exhaust ventilation system, there is usually a mechanical exhaust that is located either centrally or in a high-polluting room such as a bathroom. Air enters the dwelling through envelope leakage, open windows, or designed inlets. Because the air intake is dispersed, there is usually not any thermal discomfort associated with the system. Energy recovery can be provided with the addition of an exhaust air heat pump, but this solution may not be economical in many climates.

Although air intake through building leaks may reduce the particle concentration somewhat, intentional filtration of outdoor air is not generally possible with exhaust ventilation. In unusually tight buildings, envelope leakage may be insufficient to provide air supply, and designed intakes may be needed.

The primary advantages of exhaust systems are that the fan energy use can be kept low and the fan also has the potential to serve as source control in high-moisture locations. The primary disadvantages are depressurization of the living space (see Section 10.2.1), the lack of known distribution, and the source path of outdoor air.

10.4.5 Balanced Ventilation. In a balanced ventilation system, there is usually a mechanical exhaust either centrally located or ducted from locations likely to have high contaminant levels. There is a single outside air intake for the ventilation air, which is then dispersed through the dwelling. The systems are designed to produce equal supply and exhaust flows. With equal flows, the system creates neither pressurization nor depressurization, thus problems associated with building pressures are not introduced. Filtration and tempering of the incoming air can be accomplished at the central unit.

Most balanced systems feature either heat recovery or energy recovery. Heat-recovery systems provide thermal tempering of the incoming air using the exiting air as a source for heat (or cooling). Energy-recovery systems provide both thermal and moisture tempering of the incoming air. Energy-recovery systems use the exiting air as the source of the tempering. Either of these can be ducted independently or use ducts from a forced-air conditioning system. If the forced-air system ducts are used, it is recommended that a variable speed fan be utilized so as to reduce energy use during ventilation-only operation.

Because of its energy-recovery properties, a balanced system becomes more attractive as total space conditioning costs increase, such as in severe climates. The balanced system is also more attractive in tight homes, where mechanical ventilation is needed year-round. The balanced system is initially the most costly of the three systems, but total operating costs may be less, particularly if high-efficiency fan/motor assemblies are used.

In severe climates, the amount of tempering in the recovery device is generally limited. The designer needs to carefully evaluate the locations for outside air delivery registers to avoid discomfort.

10.4.6 Demonstrated Ventilation Alternatives. There are other ventilation strategies that can be used to meet ASHRAE Standard 62.2 if they follow good engineering practice and can be demonstrated to work appropriately for the situation.

The most common alternatives involve the use of stack- and wind-driven infiltration alone or combined with intermittent fan operation to provide equivalent ventilation. For example, a dwelling with a leaky envelope might meet the standard based on its infiltration rate under some weather conditions (generally higher indoor-outdoor temperature differentials) and meet the standard under other conditions from a combination of infiltration and mechanical ventilation.

Designed passive ventilation systems, such as passive stacks, are used in some parts of the world, such as Europe, but are not common in North America. Such systems can provide acceptable ventilation at low cost, but there are not yet any accepted prescriptive design mechanisms for use in North America. The standard allows the use of such systems within the context of a demonstrated equivalent ventilation system, as long as the designer certifies the system provides the same or lower annual exposure (refer to ASHRAE 62.2-2013, 4.6 Equivalent Ventilation[1]).

10.5 Selecting the Local Exhaust Ventilation System. Local exhaust ventilation is used to remove pollutants typically generated in the “wet rooms” of kitchens, baths, toilets, laundries, etc. Moisture and odor are major drivers, but potentially toxic airborne germs and volatile compounds are also often present. The ASHRAE 62.2 Standard[1] requires local fans to exhaust air from kitchens and bathrooms, but not toilet rooms without bathing facilities. . Exceptions are permitted in the Standard if the Alternative Compliance Path (Appendix A) is used.

The local exhaust fans may be all of, part of or none of the whole-building ventilation system. Where local fans are used, there is always a potential for significant depressurization within a space if those spaces can be closed off/sealed from the other parts of the home.

10.5.1 Mechanical Local Exhaust. Exhaust fans can be single or multiple speed and must terminate outdoors (not into buffer spaces or eave/soffit areas). In kitchens, especially those open to other rooms in the dwelling, hoods should be considered to improve capture efficiency over cooking surfaces. Recirculating range hoods do not remove most pollutants created by a cooking event and should be avoided. Extra exhaust ventilation capacity may be desirable, especially with combustion-based cooking.

Mechanical local exhaust normally is balanced by transfer air from other parts of the dwelling. For the sizes specified in the ASHRAE 62.2 Standard, they do not usually induce significant depressurization of the entire building and thus have little impact on space-conditioning costs. However, in tight dwellings or in dwellings with large exhaust flows, local exhaust can induce or cause unacceptable depressurization. Local exhaust fans usually do not affect thermal comfort adversely if the exhaust make-up air pathway is not concentrated.

Exhaust fans directly consume electricity and represent an added cost of construction. Fan noise can be an inhibiting factor in their use, but quieter, lower sone systems are available. Mechanical exhaust systems may require maintenance, such as cleaning dust off the grille, fan housing, and fan blades. The Standard requires installed local exhaust fans to be rated at three sone or less.

10.5.2 Other Local Ventilation Systems. If needed, other systems can be used to provide the local exhaust ventilation. Although not used much in North America, passive stacks and other forms of designed natural ventilation are used in some parts of the world to provide local ventilation.

Toilet flushing can aerosolize toilet water germs to create an airborne "fecal cloud".[92] Locating the bathroom exhaust vent opening 1 to 12 inches above the floor behind the toilet, rather than in the ceiling, may capture both odors and aerosolized germs from toilet water.[93] Toilet bowl exhaust ventilation can be used to directly exhaust odors and germs from the toilet bowl by keeping the toilet bowl space under negative pressure. Combinations of room exhaust location and toilet bowl exhaust ventilation are expected to minimize odor and toilet flush airborne germ exposures to occupants.

11. NATURAL VENTILATION

11.1 Introduction. Natural ventilation can provide a range of benefits for the indoor environment. At low airflow rates, it can provide for the removal of indoor air contaminants. These may be rates of one-third air changes per hour (ach) or less. At considerably higher flow rates, in the range of 30 ach, ventilation can serve to remove heat from the dwelling and thereby contribute to cooling. With very significant velocities of air flow directed across the human body (150–200 ft/min.), cooling of the body is possible.

The requirements of Standard 62.2[1] (i.e., whole-building ventilation for maintaining acceptable IAQ) can be met by mechanical ventilation at relatively low air flow rates. Ventilation for heat removal and cooling is described in *Cooling with Ventilation.*[51] This document describes methods of natural ventilation that can be used for either improvement of IAQ or cooling. This ventilation is the result of purposeful design and operation, and is not merely normal infiltration.

Because natural ventilation is driven either by indoor/outdoor temperature differences or by wind, it is variable and should to be augmented by mechanical ventilation for reliability and consistency throughout the year.

Basic natural ventilation was discussed in Section 5. This section will briefly describe alternate ventilation designs employing natural forces the can be used to complement mechanical systems.

In *A Guide to Energy Efficient Ventilation*[50], Liddament recognizes several methods: passive stack ventilation, cross-flow ventilation, single-sided ventilation, wind towers, and atria ventilation. Cross-flow and single-sided ventilation are very commonly achieved using windows/doors alone. Passive stack ventilation may be considerably more complex and may employ specifically designed ducts, passages, and openings in the building. Wind towers are a specialized and elegant form of ventilation primarily found in the Middle East and in warm

countries with reliable prevailing winds. Atria ventilation is a form of passive stack adapted to the larger scale of a multi-story atrium in a commercial building. These latter two ventilation forms will not be discussed in this guideline.

11.2 Passive Stack Ventilation. Passive stack ventilation (PSV) is driven by air density differences due to different indoor and outdoor temperatures. It is best suited to climate conditions where indoor temperatures are routinely warmer than outdoor temperatures and no air conditioning is employed. Thus, as a sole means of ventilation, it is found in locations such as Northern Europe and Scandinavia. In most of the United States outside Alaska, there are periods of the year when indoor-outdoor temperature differentials are not suitable to drive passive stack ventilation. Nonetheless, it can provide beneficial ventilation some of the time. According to Liddament, “Air flow is driven through the stack by a combination of stack pressure and wind induced suction pressure. Although the rate of air flow is variable, some control of the pattern of air flow is possible, with air predominantly entering through purpose provided ‘trickle’ ventilators and exhausted through the stack. A separate stack is needed for each room. Occasional ‘back-drafting’ will occur when the pressure generated in the stack cannot overcome the static pressure of cold outside air sitting above it.”

Axley analyzed the application characteristics of a number of passive stack ventilation (PSV) systems, primarily of European origin.[94] These include the British Specification PSV, a very representative design that is based on individual stacks that vent directly from the kitchen and bathrooms and thus, indirectly from the rest of the dwelling and that are supplied through “trickle” ventilation inlets in each exterior room. He also describes a “centralized PSV system” in which the stack draws not from the kitchen and bath, but from a central common point, such as a hall or stairwell. This system should provide more uniform ventilation for all occupied rooms of the dwelling; however, it is not recommended because it will draw air from bathroom and kitchen into other parts of the dwelling, an unwanted result. He further describes a “balanced wind stack” that provides both intake and exhaust flows through wind action from a termination at or above the roof ridgeline. Finally, he describes a “top-down chimney,” driven by thermal plumes from internal heat sources (stove, etc.).

Stacks may also be powered by wind-driven turbines or swiveling Venturi ventilators. Design information for such stacks may be obtained from manufacturers.

11.3 Cross-flow Ventilation. Cross-flow ventilation may be driven by wind or stack effect. Considerable research has been done on wind-driven ventilation. Useful resources for this are *Design with Climate: Bioclimate Approach to Architectural Regionalism*[95] *and Cooling with Ventilation*[51] from the Florida Solar Energy Center. The investigations by this organization have led to a calculation method and suggestions for advantageous window geometries, including the use of wing-walls, to best respond to winds from a given direction (Figures 11-1 and 11-2). However, for basic ventilation purposes, Chandra[51] states: “In general, for ventilating low-mass houses (e.g., frame homes or inside-insulated concrete-block homes), window location is not critical. Windows should generally be positioned as far apart as possible so that air does not short circuit between inlet and outlet.”

Two other factors are important in designing for cross-ventilation: inlets and outlets should be the same size, and there must be a clear interior path for the movement of ventilation air from inlet to outlet. Open internal pathways may be provided through the use of louvered doors, transfer ducts/grills or door undercuts. However, because the driving forces of natural ventilation are so modest, open interior doors or open-space design will probably provide the best results.

A useful approximate method for sizing openings for cross-flow ventilation is presented in *Cooling with Ventilation.*[51] It considers the actual site conditions of the dwelling and the specific weather data for the location.

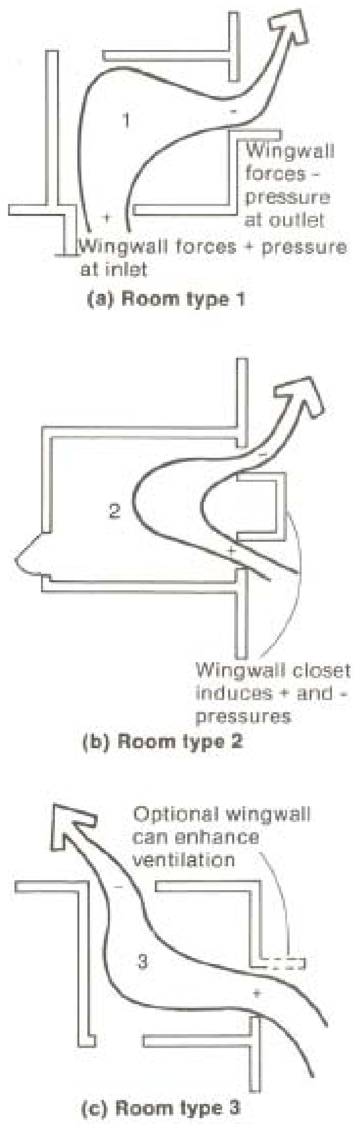

Figure 11-1 Cross ventilation, wing wall, basic patterns. (By permission of the Florida Solar Energy Center—see Reference 51.)

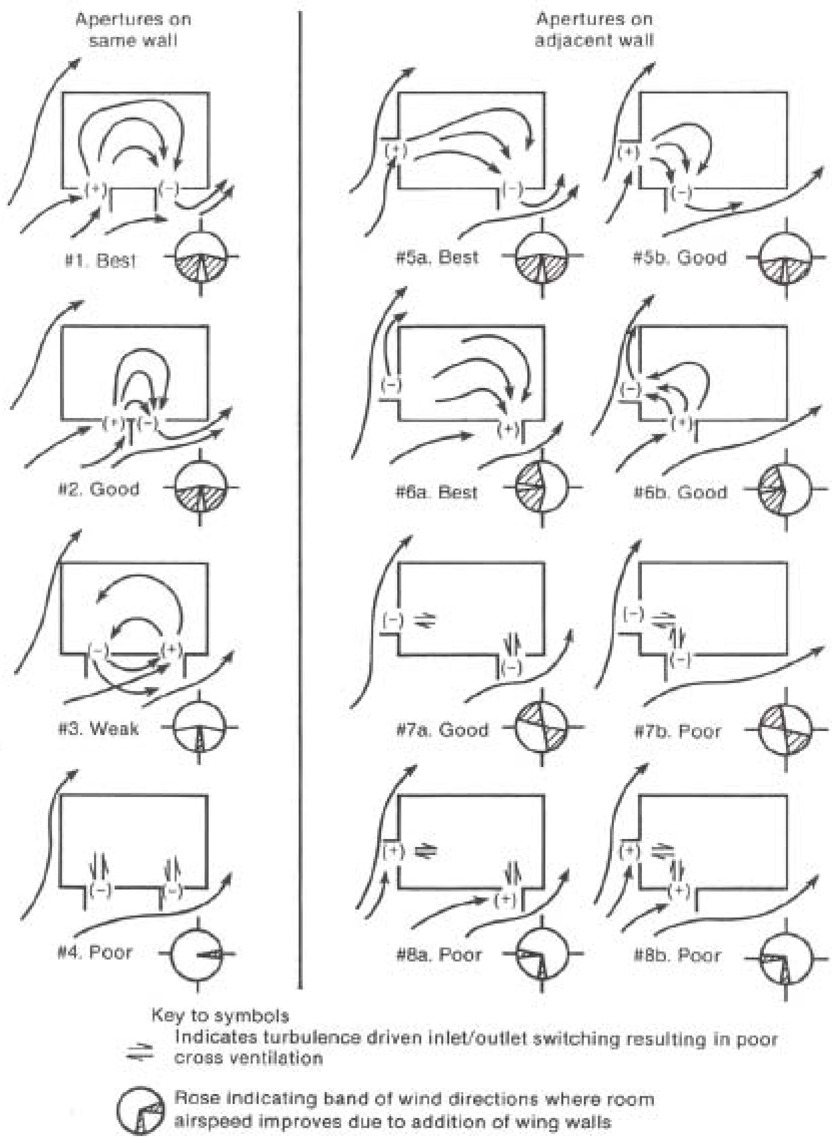

Figure 11-2 Cross ventilation, wind direction effects. (By permission of the Florida Solar Energy Center—see Reference 51.)

11.4 Design and Analysis. Because of the variability of the driving forces—wind and stack effect—rigorous design of residential natural ventilation systems would seem ill advised. In commercial structures, sophisticated computational fluid dynamics (CFD) analysis has been used, but in such systems complex flow management strategies may warrant more extensive analysis.

ASHRAE provides guidance for the basic analysis of air flow due to wind or stack effect in Chapter 16 of *Fundamentals*.[96] For airflow due to wind alone, Equation 37 of this chapter may be applied.

$$Q = 88.0 C_V A U$$

where

Q = airflow rate, cfm
C_V = effectiveness of openings (C_V is assumed to be 0.5 to 0.6 for perpendicular winds and 0.25 to 0.35 for diagonal winds)
A = free area of inlet openings, ft^2
U = wind speed, mph
88.0 = unit conversion factor

For flow caused by stack effect alone, Equation 38 may be applied:

$$Q = 60C_D A\sqrt{2g\Delta H_{NPL}\left(T_i - T_o\right)/T_i}$$

where

Q = airflow rate, cfm
C_D = discharge coefficient for opening
ΔH_{NPL} = height from midpoint of lower opening to NPL, ft
T_i = indoor temperature, °R
T_o = outdoor temperature, °R

Air flows calculated in this manner are based on the assumption of equal inlet and outlet apertures. When openings are unequal, the area of the smaller opening should be used in the calculation.

12. VERIFICATION OF EQUIPMENT PERFORMANCE

12.1 Introduction. A comprehensive system start-up process should include verifying that the system has been installed and is working according to the design specifications, as well as providing the building occupant with the information necessary to understand, operate, and maintain the system. It is critical that the residents understand the importance of the role of the ventilation system in providing acceptable IAQ, since occupants who do not understand the ventilation system are likely to attempt to shut it off permanently.

Section 4.3 of the 62.2 Standard[1] requires that the whole-building ventilation system "as installed . . . shall be measured using a flow hood, flow grid, or other airflow measuring device." Section 5.4 describes the same requirement for "Local Exhaust Ventilation".

The Heating Refrigeration and Air Conditioning Institute of Canada (HRAI) provides a detailed and comprehensive series of steps for visual verification, airflow testing, combustion-spillage testing, and documentation of ventilation and related systems.[97]

A visual verification of the ventilation system should include checking:

• Fan and ventilator mounting;
• Ducts are properly mounted, that flex ducts are stretched tight, joints are taped or sealed, ducts running through unheated spaces are insulated , there are no tears or unsealed joints in the vapor barriers, the ducts connected where they should be, and any operable dampers are open;
• Grilles are properly secured;
• Filters are installed where necessary;
• Exhaust outlets from the building are above grade and snow level;
• Air intakes (heat recovery ventilator [HRV], energy recovery ventilator [ERV] or supply ventilation) are labeled as such and not located near a potential pollution source, such as a driveway, combustion exhaust, or garbage storage;
• Bird screen installed on the air intake;
• Electrical connections are properly made;
• Controls are marked and accessibly located;
• HRV/ERV drains are properly installed;
• Filters are in place, readily accessible, and marked;
• Connections to a forced air system are properly made; and
• System documentation is provided.

Functional/observational testing of the system will ensure that the system is functioning and being controlled. This can be as simple as:

• Turning the system on and listening for unexpected noises;
• Sensing the airflow at any inlets or outlets with a hand (inside and outside the dwelling if the system is an HRV/ERV);
• Adjusting and sensing the system performance at high and low speed;
• Checking for duct leakage;
• Operating a humidistat or other control by raising or lowering the set point to determine variations in flow; and
• Testing the functionality of any special controls including interlocks with the HVAC distribution system if necessary.

12.2 Flow Testing.[98] In order to provide consistent, comparable performance, ventilation products are tested and certified for performance in a laboratory under repeatable conditions. Fans are tested for airflow performance by the HVI 916 Standard[99] at 0.1 in. w.c. Some manufacturers have their fans tested at higher static pressures, also, commonly 0.25 in. w.c. The 0.1 in. w.c. rating is what is usually listed on the fan packaging. Fans are tested as they are manufactured, including the grille, the fan system, and damper. Actual installed system static pressure drop is likely to be much greater than the static pressure at which the fan was tested by the manufacturer. For this reason, the 62.2 Standard requires that installed system performance be measured. Fan performance specifications do not include any ductwork or terminal fitting (hood); these will provide considerable resistance to actual airflow, but the degree varies from application to application. The results of the flow testing should be recorded on the System Documentation Forms (see Section 13) and compared to the required design flows.

12.2.1 Exhaust or Supply Fan Flow Testing. Flow testing should take place after the fan is fully installed, attached to its ductwork and exterior termination. Flow dampers should be in

place and functional, and controls should be activated. The house should be set up in “winter conditions” with all the exterior doors and windows closed. Other air moving equipment, such as an air handler, clothes dryer, combustion equipment, or other ventilating products should be turned off before performing the tests. If the fan will operate at multiple speeds, performance should be tested at the highest and the lowest flow rates.

In the case of an exhaust fan, the pathway of the air into the dwelling, through the fan, and to the outside will impact the fan’s performance. Closing a bathroom door, for example, may cut the flow through the fan significantly. The tested performance for a local exhaust fan generally will be with the bathroom door closed. The tested performance for a whole-building fan generally will be with the bathroom door open.

12.2.2 HRV or ERV Fan Flow Testing. Heat or energy recovery ventilators should be balanced as a part of their installation. The air being drawn in from the outside should equal the air exhausted. If the system is unbalanced, its heat or energy transfer efficiency will be compromised.

The system should be balanced according the manufacturer’s instructions. This is commonly done by installing a “flow grid” in the supply and exhaust ducts, measuring the pressure with an analog or digital gauge, and adjusting balancing dampers until the flows are equal. Balanced flow is much simpler to achieve when the HRV or ERV has an independent duct system, rather than one attached to house’s heating/cooling ductwork. If the HRV or ERV is connected to the dwelling’s air handler, the impact of the air handler’s blower should be evaluated when balancing the flows through the recovery ventilator.

If the HRV or ERV has its own flow taps, the flow through the system can be measured using the system’s corresponding flow chart, or measured at each supply register and totaled.

12.2.3 Measuring Airflow Through Inlets. An inlet to the return side of the air handler ductwork will draw outside air into the house whenever the air handler fan is running. Some of these systems include controls that activate a motorized damper that will allow in the flow of a specific amount of air, activating the air handler for ventilation even when it is not required to run for heating or cooling. Some systems also include an outside sensor that will prevent the damper from operating if the outside humidity is too high. Systems might also include a passive damper that varies the size of its aperture depending on the pressure of the system airflow. Before testing can be accomplished, the damper should be open and the air handler should be running.

One measurement approach for these systems is to measure the flow through the exterior termination hood. If it is accessible and the surface of the surrounding wall is reasonably smooth so that a flow hood can be installed tightly over the termination fitting, this is the simplest approach.

A second approach is to drill a hole in the duct leading to the air handler and use a hot wire or mini-vane anemometer to take a series of five readings across the duct. By averaging the

readings and multiplying the result by the area of the duct, the cubic feet of air moving through the duct can be calculated.

A third approach is to use a pitot tube and a digital or analog gauge. The two taps on the pitot tube can be connected to the two ports on the manometer resulting to measure the velocity pressure. (Some of the digital gauges provide a direct reading of the velocity.) The velocity can then be multiplied by the area of the duct to arrive at the rate of airflow.

Finally, by drilling into the duct, the operating pressure can be measured. The duct can then be disconnected from the return plenum and connected to a calibrated fan or duct testing device. The flow through the duct tester should be increased until the pressure through the system is equal to the operating pressure previously measured. At that point the flow through the calibrated fan will equal the flow through the assembled system.

12.2.4 Flow Hood Testing. There are a variety of flow hoods that can be used to measure airflow. Some of use a flow grid of evenly spaced sensing ports that sample air movement across the flow. Some of them use the spinning of a vane. Most of these devices have direct digital readouts reporting airflow.

If the flow hood has an adjustable capture hood, it should be sized to closely match the size of the opening being measured otherwise substantial recirculation regions on the sides of the fabric hood may cause uneven airflow patterns that reduce the accuracy of the flow reading.

Additionally, there are large vane anemometers that mount in specially designed capture hoods or funnels. The airflow is guided through the funnel, causing the vane to spin. These devices can automatically display the airflow volume.

12.2.5 Hot Wire or Mini-Vane Anemometer Testing. A hot wire or mini-vane anemometer can be used to measure the airflow velocity through a grille. Multiplying the velocity by the area of the grille opening can provides the flow rate. Readings should be taken at multiple points across the opening so that an average airflow can be determined. Calculating the actual opening of the grille is not a simple task because of the multiple struts and louvers. Readings are commonly higher than the actual flow rate. In general, it is not recommended to use this method because of the variability of the flow rate at different locations and the difficulty in estimating the actual open area of the grille.

12.2.6 Passive Exhaust Fan Flow Hoods. Using a box with an adjustable opening of a known area and a pressure tap in one corner, can provide a relatively accurate flow reading for exhaust flow. The airflow through the known hole size can be calculated if the pressure difference across the hole is known. These devices are nominally accurate between airflow rates of 10 to 125 cfm. This relationship can be expresses as:

$$Q=1.07 \text{ x } A \text{ x } (\Delta P)^{0.5}$$

where

Q = airflow in cfm
A = the area of the hole in square inches
ΔP = the difference in pressure in Pascals

12.2.7 Powered Flow Testing. A calibrated fan with an airflow ring, a manometer, and an extension duct attached to a flow box will accurately measure the flow through a ventilation fan by offsetting any resistance that might normally be associated with the flow measuring device. The flow box should be sealed over the fan opening. The flow through the instrumented fan is increased until the difference in pressure in the flow box is zero or the same as the surrounding room pressure. At this point, the flow through the instrumented fan and the fan being tested will be the same, and the reading of the flow through the instrumented fan can be read from the companion manometer/flow calculator.

Another approach to this is an all-in-one system (without the ductwork) that includes an instrumented fan and a companion manometer that automatically controls the flow through the fan, displaying the flow when the flow through the instrumented fan and the fan being tested are the same.

13. OPERATIONS AND MAINTENANCE DOCUMENTATION

13.1 Introduction. This section provides general guidance regarding the minimum operations and maintenance information to be provided by the ventilation system designer or installer. It is recommended that this material be placed in a binder along with equipment installation information, warranties, and homeowners manuals and be given to the owner/occupant of the dwelling. A Homeowners O&M Documentation Form is provided on the next page to summarize the essential information for the homeowner or occupant.

Many mechanical ventilation systems require occupant interaction to work as intended. It is important that the building occupants are informed as to the function of the individual components and what they are expected to do. This is especially important when systems are logically, but not physically coupled, when safety issues are involved, or when the components are multifunctional and may not be easily recognized as part of a designed ventilation system. Labels can help the homeowner understand the ventilation system.

Part of this documentation should be the measured airflow performance of the system upon installation. This will be useful for verifiers such as HERS raters or EnergyStar verifiers who need to know how the system was designed to perform

13.2 Operation Documentation. Written information on the proper and expected operation of the ventilation system chosen for compliance with Chapters 4, 5, 6, and 7 of the 62.2 Standard[1] should be provided, including the parameters assumed by the ventilation system designer. This system operation information should cover all mechanical ventilation equipment, ventilation controls, and any passive or natural ventilation devices used to comply with the Standard.

System Design:

<table>
<tr><td>Floor Area</td><td># of bedrooms +1</td><td colspan="3">cfm or L/s

(calculation or from table 4.1)</td></tr>
<tr><td></td><td></td><td colspan="3"></td></tr>
<tr><td>Combustion cfm Threshold</td><td>15 cfm/100 square feet</td><td colspan="3"></td></tr>
<tr><td>Combustion Appliances</td><td>Location</td><td colspan="3">Installed outdoor air supply (yes/no/NA)</td></tr>
<tr><td>DHW</td><td></td><td>Yes</td><td>No</td><td>NA</td></tr>
<tr><td>Furnace</td><td></td><td>Yes</td><td>No</td><td>NA</td></tr>
<tr><td>Boiler</td><td></td><td>Yes</td><td>No</td><td>NA</td></tr>
<tr><td>Fireplace</td><td></td><td>Yes</td><td>No</td><td>NA</td></tr>
<tr><td>Other (stove, oven, etc.)</td><td></td><td>Yes</td><td>No</td><td>NA</td></tr>
</table>

Whole-Building Ventilation System Type:

<table>
<tr><td>System Choice</td><td>✓</td><td>Date Installed</td><td colspan="3">System Location</td><td>Balanced @ Install ✓</td></tr>
<tr><td>Exhaust-only</td><td></td><td></td><td colspan="3"></td><td>NA</td></tr>
<tr><td>Supply-only</td><td></td><td></td><td colspan="3"></td><td>NA</td></tr>
<tr><td>Balanced w/o heat or energy recovery</td><td></td><td></td><td></td><td># supplies</td><td># returns</td><td></td></tr>
<tr><td>Heat recovery ventilator</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Energy recovery ventilator</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Supply to air handler</td><td></td><td></td><td colspan="3"></td><td>NA</td></tr>
</table>

Ventilation Product Information:

Brand	**Model ID**	**Required Airflow**	**Total Installed Airflow**	
			Normal	**Boost**

Controls:

Brand	**Model ID**	**Function (Multi-speed, intermittent, etc.)**

Whole-Building Ventilation System Function and Operating Instruction:

Required Maintenance (Annual or seasonal recommended as a minimum):

Local Ventilation System Type:

System Choice	✓	**Date Installed**	**System Location**			**Quantity**
Exhaust-only						
Balanced w/o heat or energy recovery				# supplies	# returns	
Heat recovery ventilator						

Energy recovery ventilator						
Supply to air handler						

Ventilation Product Information:

Location	**Brand**	**Model ID**	**Required Airflow**	**Installed Airflow**	
				Normal	**Boost**
Kitchen					
M Bath					
Bath 2					
Bath 3					
Bath 4					

Controls:

Location	**Brand**	**Model ID**	**Function**
Kitchen			
M Bath			
Bath 2			
Bath 3			
Bath 4			

Local exhaust Ventilation System Function and Operating Instruction:

Required Maintenance (Annual or seasonal recommended as a minimum):

System designer contact name and numbers:

Company Name

Contact Person

Street, City, State, Zip

Office phone

Cell phone

E-mail

Installing contractor contact name and numbers:

Company Name

Contact Person

Street, City, State, Zip

Office phone

Cell phone

E-mail

13.2.1 Design and Operation Parameters

• Installing contractor contact name and numbers
• Heating/cooling load calculations
• Ventilation calculations
• As-built drawings
• Any required energy calculations
• Any combustion safety calculations or requirements
• Permit documentation
• Clear statement of type of ventilation approach being used (natural, continuous mechanical, or intermittent mechanical)
• Operating schedule

13.2.2 Mechanical Ventilation Equipment

• Operation, maintenance, and installation/owner's manuals from manufacturer

• Make, model, size, and supplier for all equipment
• Operating range
• Electrical requirements
• Emergency contact names and numbers

13.2.3 Natural and Passive Ventilation Devices

• Operation, maintenance, and installation/owner's manuals from manufacturer
• Make, model, size, and supplier for all devices
• Operational requirements/schedule of operation by the occupant to ensure acceptable IAQ
• Limitations on the acceptability of IAQ if natural ventilation devices are not operated as intended

13.2.4 Ventilation Controls

• Operation, maintenance, and installation/owner's manuals from manufacturer
• Make, model, size, and supplier for all equipment
• Control strategy and description

13.3 System Maintenance. Homeowners should be made aware of how their system was designed to run when the contractors completes the installation and commissioning. They should also be made aware of any maintenance required in the written information that is provided. Over the years, the use of the dwelling is likely to change, so changes may need to be made to the operation of the ventilation system. Its initial configuration may no longer meet the needs of the current occupants.

Many homes are built very tightly. They rely on the ventilation system to change the air, to dilute the pollutants, and keep the house and its occupants safe and healthy. If birds have nested in the exhaust ducts, the air cannot move out of the house. If a very quiet fan has stopped running, the homeowner may not even notice it. Fans are mechanical systems and no matter how well they have been crafted, manufactured, and installed, they will break at some point. They need to be accessible for servicing and they need to be serviced. The more complex the system the more maintenance will be required.

13.3.1 Exhaust Fan System Maintenance. There are not many maintenance issues with an exhaust fan mounted in the ceiling or in the line of a duct. As an exhaust fan, there is no filter to change and most of the motors are sealed and don't need oiling. If the fan works and moves air, clean the grille and the fan blades when required. Follow the manufacturer's instructions if they are available. The exhaust termination fitting should be checked to make sure that no birds are nesting in it and that the backdraft damper is working properly. If the weather hood is cracked or broken, it should be replaced to keep the wind and the rain out. If the ducting is accessible, it should be checked to be sure that it is not crushed or full of water. If it is uninsulated and running through an unconditioned space, it should be replaced with insulated ducting. Replacing small diameter duct with a larger diameter and straightening out the twists, turns, and kinks will improve the airflow.

Remote-mounted or in-line fans can collect condensation inside their housings if they have been mounted horizontally. A drain can be added, and if they have been installed for more than five years, taking the fan apart and cleaning it is advisable.

13.3.2 HRV/ERV Maintenance. HRV/ERVs have more components and require more attention. Manufacturers are the primary resource for information on the appropriate maintenance steps. The system should be located where the housing can be opened and the components can be serviced. The filters need to be cleaned and/or replaced regularly. The core should be removed from the housing and cleaned. Both fans should be checked to be sure they are running. (This can be verified by checking if the system is balanced.)

Check the condensate drain and pans. Make sure they are not blocked and the pans are clean. Make sure that there is a proper trap in the drain.

Check on the exterior termination hoods and make sure they are not blocked or do not have plants, leaves, or snow piling up in front of them. Make sure animals are not living in them and that protective screens are still in place. Check the backdraft damper on the exhaust fitting. Make sure there are no contaminant sources like trash cans or rotting leaves near the fresh-air intake.

Check the ducting for poorly taped connections, poor sealing of vapor barriers, missing insulation, compressed ducting, poorly sized ducting or meandering runs.

Check the defrost system. The defrost cycle in most systems activates when the temperature of the incoming air drops below 25ºF (-5ºC). Some systems have an internal motorized damper that temporarily blocks incoming fresh air, allowing only house air to circulate and defrost the core.

Check the functions of the control system and make sure it is controlling the airflows as required.

13.4 Maintenance Documentation. Written information on the required maintenance of the ventilation system components chosen to comply with Chapters 4, 5, 6, and 7 of the 62.2[1] Standard should be provided, including any mechanical or passive components and controls. Maintenance information should include any information provided by the ventilation equipment manufacturers.

13.4.1 Mechanical Ventilation Equipment

- Maintenance contractor contact name and numbers
- Filter cleaning/replacement schedule

13.4.2 Natural Ventilation Devices

- Inspection requirements to ensure that inlets and outlets will operate (e.g., not painted shut)
- Any required maintenance for the devices

13.4.3 Ventilation Controls

• Any required maintenance for the controls
• Troubleshooting and reset methods for the controls

13.4.4 Building Envelope. Whether intended or otherwise, the building envelope is part of the ventilation system. The building envelope should be maintained to operate as intended.

Ventilation make-up air, such as air inlets, is required and installed in many buildings. In addition, combustion air from outside the structure should be provided in accordance with the *National Fire Protection Association 31, Standard for the Installation of Oil-Burning Equipment*[100], *NFPA 54/ANSI Z223.1, National Fuel Gas Code*[101], and *NFPA 211, Standard for Chimneys, Fireplaces, Vents, and Solid-Fuel Burning.*[102] If credit for infiltration is taken, the building envelope air leakage is part of the ventilation. In such cases, the requirements of the standard should be reviewed whenever envelope tightening is considered.

Without proper maintenance, the building envelope tightness may degrade over time. Excessive building leakage can cause increased energy use and can unbalance some mechanical ventilation systems. Excessive leakage can also allow moisture into the envelope, which may lead to damage and loss of serviceability. (See the *American Society for Testing Materials E241-09, Standard Guide for Limiting Water-Induced Damage to Buildings*[103] for more details.)

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15. ABBREVIATIONS

BEIs: biological exposure limit

OSHA: Occupational Safety and Health Administration (U.S.A.)

STEL: short-term exposure limit

TLVs: threshold limit values

TWA: time weighted average

POLICY STATEMENT DEFINING ASHRAE'S CONCERN FOR THE ENVIRONMENTAL IMPACT OF ITS ACTIVITIES

ASHRAE is concerned with the impact of its members' activities on both the indoor and outdoor environment. ASHRAE's members will strive to minimize any possible deleterious effect on the indoor and outdoor environment of the systems and components in their responsibility while maximizing the beneficial effects these systems provide, consistent with accepted standards and the practical state of the art.

ASHRAE's short-range goal is to ensure that the systems and components within its scope do not impact the indoor and outdoor environment to a greater extent than specified by the standards and guidelines as established by itself and other responsible bodies.

As an ongoing goal, ASHRAE will, through its Standards Committee and extensive technical committee structure, continue to generate up-to-date standards and guidelines where appropriate and adopt, recommend, and promote those new and revised standards developed by other responsible organizations.

Through its *Handbook* ASHRAE will take the lead with respect to dissemination of environmental information of its primary interest and will seek out and disseminate information from other responsible organizations that is pertinent, as guides to updating standards and guidelines.

The effects of the design and selection of equipment and systems will be considered within the scope of the system's intended use and expected misuse. The disposal of hazardous materials, if any, will also be considered.

ASHRAE's primary concern for environmental impact will be at the site where equipment within ASHRAE's scope operates. However, energy source selection and the possible environmental impact due to the energy source and energy transportation will be considered where possible. Recommendations concerning energy source selection should be made by its members.